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**ELECTRONICS-X: A STUDY OF MILITARY
ELECTRONICS WITH PARTICULAR REFERENCE
TO COST AND RELIABILITY. VOLUME 2:
COMPLETE REPORT**

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Institute for Defense Analyses

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report identifies the current DOD and industrial policies, procedures, and practices in development, production, and operational support that most significantly influence the cost and reliability of military electronics, and it recommends changes to reduce and control cost and to improve reliability. The report concentrates on five major, high-impact areas: (1) data		

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19. data processing software, digital system architecture, design evolution, configuration management, project management, data costs, cost estimating
20. collection and feedback, (2) requirements, (3) competition and management options, (4) reliability enhancement, and (5) maintenance training. Numerous other areas are discussed, and detailed recommendations are made in each.

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PREFACE

The Electronics-X study program was conducted by the Institute for Defense Analyses (IDA) with the able assistance of representatives of industry, private research organizations, and Government, as well as private consultants. The members of the study team were:

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Additional outside assistance on one phase of the work--avionics computer standardization--was obtained under subcontract with System Development Corporation (SDC), Santa Monica, California. Corlin O. Beum was the SDC program manager for this effort; Eugene Levin was the principal investigator.

STEERING GROUP

The effort was guided by Jacques S. Gansler, Assistant Director for Planning, Office of the Director of Defense Research and Engineering (ODDR&E) and a Department of Defense (DOD) steering group chaired by Mr. Gansler. The membership of the steering group was as follows:

Jacques S. Gansler (Chairman)	Assistant Director (Plans), ODDR&E
Herbert D. Benington	Deputy Director (Information and Space Systems), ODDR&E
RADM Stanley T. Counts, USN	Deputy Commander for Systems and Acquisition, Naval Ordnance Sys- tems Command
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ADVISORY COMMITTEE

Periodic critical review of the work was provided by an IDA Advisory Committee, whose membership was:

James J. Bagnall	Institute for Defense Analyses
William Carnes	Aeronautical Radio, Incorporated
Harry Davis	Consultant
Marvin E. Lasser	Chief Scientist, Department of the Army
Joel S. Lawson	Director, Navy Laboratories
Peter Murray	Consultant
Charles H. Phipps	Texas Instruments, Incorporated
Donald G. Richards/ Charles Brahm	United Aircraft Corporation

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Valuable contributions of assistance and information were made by a number of industrial organizations:

Aeronautical Radio, Incorporated	The Boeing Company
Aerospace Systems Division, The Bendix Corporation	Collins Radio Company
	Electronic Industries Association

General Dynamics Corporation	Motorola, Incorporated
General Electric Company	Northrop Corporation
Hughes Aircraft Company	RCA Corporation
IBM Corporation	Rockwell International Corporation
International Telephone and Telegraph Corporation	Kearfott Division, The Singer Company
Kaiser Aerospace and Electronics Corporation	Texas Instruments, Incorporated
Litton Industries	TRW, Incorporated
McDonnell Douglas Corporation	United Aircraft Corporation
	Westinghouse Electric Corporation

In addition, the materiel and headquarters organizations of the Army, Navy, and Air Force gave much assistance and information and critiqued the initial, very tentative, conclusions and recommendations. The Army also provided three individual participants (listed previously) who contributed directly to the study effort.

Robert H. Fox of IDA provided helpful technical discussion and performed a detailed review and constructive critique of the several drafts of this report.

STUDY ORGANIZATION

The Electronics-X Study was organized by the groupings into which fell the many remedial recommendations received during the organizational phase and the early study effort. These groupings, and the corresponding group leaders, were:

- Requirements and Pre-Acquisition Decisionmaking--
Seymour J. Deitchman
- Design to Cost--Joel Norman
- Standardization--Robert Polkinghorn
- Cost and Schedule Estimating; Cost Allocation--C. David Weimer
- Reliability--Myron Wilson; Max Tall
- Maintenance and Training--Thomas Rowan
- Warranties--David Arnold

- Incentives--David Soergel; Wayne Allen
- ASPRs and Statutes; Legal Constraints--Howard Zimmerman.

Three additional topics later emerged as important and are treated in this report:

- Design Evolution and Configuration Management
- Software; Digital System Architecture
- Project Management.

EPOCH

The Electronics-X study program was organized during the period October 1, 1972 to January 31, 1973. The main study effort commenced February 1, 1973 and concluded July 31, 1973. Current results were presented to and discussed with the Defense Science Board Task Force on Electronics Management at its meeting at Woods Hole, Massachusetts, August 6-17, 1973. Preparation of this report began subsequent to that meeting.

REPORT FORMAT AND PREPARATION

This report is published in two volumes. The first volume, Executive Conspectus, is designed to present a rapid overview of the reasons for the Electronics-X Study, the problems addressed in the study, and the principal findings and recommendations. The second volume contains the complete report, comprising the contents of the Executive Conspectus plus detailed analyses, discussion, and backup information.

As a product of the main study, a series of Electronics-X working papers were generated. Those papers formed a basis for this report. They are available in the IDA Library to readers who wish to pursue specific subjects in greater detail.

This report was prepared by Gates, Gourary, Deitchman, Rowan, and Weimer. B. Roberts served as editor.

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ABBREVIATIONS

AA	American Airlines
AABNCP	advanced airborne command post
AACOMS	Army Area Communications System
AADC	Advanced airborne digital computer
AAH	advanced attack helicopter
ABNCP	airborne command post
A/C	aircraft
ACSFOR	Assistant Chief of Staff for Force Development
ADO	Advanced Development Objective
ADP	Advanced Development Proposal
APP	Army procurement procedure
AECOM	Army Electronics Command
AEEC	Airlines Electronic Engineering Committee
AEW	airborne early warning
AFETS	Air Force Engineering Technical Service
AFHRL	Air Force Human Resources Laboratory, AFSC
AFLC	Air Force Logistics Command
AFM	Air Force manual
AFR	Air Force regulation
AFSC	Air Force Systems Command
AGARD	Advisory Group for Aeronautical Research and Development
AGE	aerospace ground equipment
AGED	Advisory Group on Electronic Devices
AIMS	ATCRBS IFF Mark XII System
AMA	Air Materiel Area
AMC	Army Materiel Command
AMICOM	Army Missile Command

AMPLAF	amplifier, audio frequency
ANA	Air Force-Navy Aeronautical
A _O	operational availability
AR	Army regulation
ARPA	Defense Advanced Research Projects Agency
ARTADS	Army Tactical Data System
ASC	Advanced System Concept
ASD	Assistant Secretary of Defense
ASD(I&L)	Assistant Secretary of Defense (Installations & Logistics)
ASD(T)	Assistant Secretary of Defense (Telecommunications)
ASO	Aviation Supply Office
ASPR	Armed Services Procurement Regulation
ATA	Air Transport Association
ATACS	Army Tactical Communication System
ATBF	air time between failures
ATCRBS	Air Traffic Control Radar Beacon System
ATI	air transport industry
AVG	average
A-VIS	audio-visual information system
AWACS	airborne warning and control system
BCD	binary coded decimal
BFIC	binary fault isolation chart
CAMESA	Canadian Military Electronics Standards Agency
CC	command and control
CCB	Change Control Board
CCDR	Contractor Cost Data Report
CER	cost-estimating relationship
CFSR	Contract Funds Status Report
CI	configuration item
CIR	Cost Information Report
CM	countermeasure

CMW	contractor maintenance warranty
CNI	communications, navigation, and identification
CONARC	United States Continental Army Command
CONUS	continental United States
CP	command post
CPAF	cost plus award fee
CPIF	cost plus incentive fee
CPR	Cost Performance Report
CPU	central processing unit
DCP	Decision Coordinating Paper, formerly Development Concept Paper
DDT&E	design, development, test, and evaluation
DDR&E	Director of Defense Research and Engineering
DECM	defensive electronic countermeasure
DIR	Disassembly and Inspection Report
DME	distance measuring equipment
DOD	Department of Defense
DP	development plan
DRAG	Data Review Action Group (Air Force)
DSA	Defense Supply Agency
DSARC	Defense Systems Acquisition Review Council
DSU	direct support unit
DTC	design to cost
DT&E	development, test, and evaluation
ECM	electronic countermeasure
ECP	engineering change proposal
ED	engineering development
EDP	Engineering Development Proposal
EIA	Electronic Industries Association
EIR	Equipment Improvement Request (Army); Engineering Investigation Request (Navy)
E/O	electro-optical
ER	extended range

ESD	Electronic Systems Division, AFSC
ESP	Electronic Standards Panel
EUMR	Emergency Unsatisfactory Material Report
EUR	Emergency Unsatisfactory Report
EW	electronic warfare
FAA	Federal Aviation Agency
FADAC	field artillery data computer
FFW	"failure-free" warranty
FICA	Federal Insurance Contributions Act
FLIR	forward-looking infrared
FP	fixed price
FSN	Federal stock number
FY	fiscal year
FYDP	Five Year Defense Program
G&A	general and administrative
GAO	General Accounting Office
GEMM	Generalized Electronics Maintenance Model
GIDEP	Government-Industry Data Exchange Program
GNP	gross national product
GOR	general operational requirement
GP	general purpose
GSE	ground support equipment
GSU	general support unit
GTV	guided test vehicle
HF	high frequency
Hq	headquarters
HumRRO	Human Resources Research Office
HV	high voltage
ICBM	intercontinental ballistic missile
IDA	Institute for Defense Analyses

IFF	identification, friend or foe
I&L	Installations and Logistics
ILS	instrument landing system
IMPACT	Improved Management of Procurement and Contracting Techniques (Army)
INH	inherent
INS	inertial navigation system
I/O	input/output
IOC	initial operational capability
IPCE	independent parametric cost estimate
IR	infrared
IROS	Increase Reliability of Operational Systems (Air Force)
JCS	Joint Chiefs of Staff
JPA	job performance aid
LAMPS	light airborne multi-purpose system
LANTFLT	United States Atlantic Fleet
LC	life cycle
LCC	life-cycle cost
LCSC	life-cycle support cost
LGB	laser-guided bomb
LORAN	long-range navigation
LRIP	low-rate initial production
LRU	line replaceable unit
LSI	large-scale integration (integrated)
MAC	maintenance allocation chart; Military Airlift Command
MAINT	maintenance
MANPAD	Man-Portable Air Defense (System)
MBT	main battle tank
MDC	maintenance dependency chart
MDCS	maintenance data collection system

MDS	malfunction detection system
MDT	mean down-time
MFHBF	mean flight hours between failures
MIL SPEC	military specification
MIL STD	military standard
MIPR	Military Interdepartmental Purchase Request
MK	mark
MMHTR	mean man-hours to repair
MN	materiel need
MOS	metal oxide semiconductor; military occupational specialty
MPA	military personnel appropriation
MR	medium range
MSI	medium-scale integration (integrated)
MTBF	mean time between failures
MTI	moving target indicator
MTTR	mean time to repair
MUX	multiplex
NAFI	Naval Avionics Facility Indianapolis
NAIR	Naval Air Systems Command Headquarters
NARF	Naval Air Rework Facility
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NAVELEX	Naval Electronic Systems Command
NAVMATINST	Naval Material Instruction
NAVORD	Naval Ordnance Systems Command
NAVSHIPS	Naval Ship Systems Command
NMC	Naval Material Command
NORM	nonoperational-readiness days due to maintenance
NORS	nonoperational-readiness days to supply
NTDS	Naval Tactical Data System
OASD	Office of the Assistant Secretary of Defense

ODDR&E	Office of the Director of Defense Research and Engineering
O&I	organizational and intermediate
OJT	on-the-job training
O&M	operation and maintenance
OMB	Office of Management and Budget
OPR	operational
ORG	organizational
OSC	oscillator
OSD	Office of the Secretary of Defense
OT&E	operational test and evaluation
OTH	over the horizon
PACFLT	United States Pacific Fleet
PERT	Program Evaluation and Review Technique
PIMO	Presentation of Information for Maintenance and Operations
PIR	Procurement Information Report
PM	project manager
PMD	Program Management Directive
PMP	Program Management Plan
POL	petroleum, oil, and lubricant
QMR	qualitative materiel requirement
RADC	Rome Air Development Center, AFSC
RAM	reliability, availability, and maintainability
R&D	research and development
RDTE&E	research, development, test, and evaluation
REWSON	Reconnaissance Electronic Warfare Special Operations Naval Intelligence Systems Project
RF	radio frequency
RFP	request for proposal
ROC	required operational capability
ROM	read only memory

RPM	reliability planning and management
RTCA	Radio Technical Commission for Aeronautics
SAGE	semi-automatic ground environment
SAM	surface-to-air missile
SASI	ship and air systems integration
SAR	Selected Acquisition Report
SATCOM	satellite communications
SDC	System Development Corporation; sample data collection
SEA	Southeast Asia
SECDEF	Secretary of Defense
SIMM	symbolic integrated maintenance manual
SLBM	sea-launched ballistic missile
SM	Standard Missile
SMRS	Source Maintenance and Recoverability Standard
SOP	standard operating procedure
SOR	specific operational requirement
SPEC	specification
SPO	system project office; special projects office
SRA	specialized repair activity
SSB	single sideband
SSM	surface-to-surface missile
STOL	short takeoff and landing
SUP	support
TAC	Tactical Air Command
TACAN	tactical air navigation
TACFIRE	Tactical Fire Direction System
TAMMS-Aviation	The Army Maintenance Management System--Aviation
TAMMS-SDC	The Army Maintenance Management System--Sample Data Collection
TDY	temporary duty
TM	technical manual
TO	technical order
TOW	tube-launched, optically tracked, wire-guided antitank missile

TRACALS	Traffic Control and Landing System
TSO	Technical Standard Order
TSOR	Tentative Specific Operational Requirement
TYCOM	type commander
UHF	ultrahigh frequency
UMR	Unsatisfactory Material Report
UR	Unsatisfactory Report
USA	United States Army
USAF	United States Air Force
USARAL	United States Army, Alaska
USAREUR	United States Army, Europe
USARPAC	United States Army, Pacific
USMC	United States Marine Corps
USN	United States Navy
UTTAS	Utility Tactical Transport Aircraft System
VAST	Versatile Avionic Shop Test (System)
VNAF	Vietnamese Air Force
VOR	VHF omnidirectional range
VORTAC	VHF omnidirectional range/tactical air navigation
VSTOL	vertical and/or short takeoff and landing
WBS	work breakdown structure
WRA	weapons replaceable assembly
WUC	work unit code
WX	weather
3M	Maintenance and Material Management System (Navy)

I. SYNOPSIS, FINDINGS AND RECOMMENDATIONS

A. SYNOPSIS

Rising acquisition costs, poor field reliability of military systems, shrinking quantities of weapons--these are the symptoms that impelled the Director of Defense Research and Engineering to initiate the Electronics-X Project at IDA with the purpose of reviewing the process of acquisition and maintenance of military electronics and recommending specific policies and procedures to remedy the situation. The magnitude of military electronics, its pervasive nature, and its rapid growth led to its being singled out as an area in which massive savings might be achieved.

Out of a total DOD FY 74 budget of \$81.1 billion, electronics outlays total \$15.3 billion. They can be categorized as follows:¹

	<u>Billions</u>
Electronics RDT&E	\$ 4.1
Electronics Procurement	5.8
Electronics Support	5.4
Electronics Total	<u>\$15.3</u>

The increasing complexity and parts count of weapons systems electronics have caused declines in system reliability in spite of the growth in reliabilities of individual electronic parts. The annual support costs for military electronics are now almost equal to the annual procurement costs and constitute more than one-third of all annual expenditures on military electronics. Since military maintenance is labor intensive, the increase in military compensation

designed to achieve and maintain comparability with civilian wages can be expected to further inflate the costs of electronics support.

The charter for Electronics-X called for recommendations that could be readily translated into implementable policies, procedures, and practices. The study took into account broad principles recommended by earlier investigations and sought specific data leading to suggested approaches to a reduction of the costs of electronics acquisition and support that would be consistent with the role of military electronics: enhancing the combat capability and crisis readiness of military forces.

The study identified problem areas, assessed the magnitude of the problems, attempted to determine their principal causes, and then formulated recommendations for eliminating, as far as possible, those causes. Obviously, then, the recommended courses of action are not unique solutions of the problems but rather represent the consensus of best judgments of the Study Group. Some of the recommendations necessarily call for an experimental or evolutionary approach to solving particular aspects of problems, since the response to major changes in operating procedures of the complex DOD R&D, procurement, and support apparatus, and in the interaction of that apparatus with suppliers, cannot be predicted with confidence. The process of achieving improvement is one requiring feedback data and corrective action as it proceeds. Thus, the need for innovative, aware, and responsive management plays a very important part in the recommendations. It is believed that the indicated directions of change clearly counter some of the major causes of problems in electronics cost and reliability and constitute reasonable initial steps in the evolutionary process.

This report is concerned with three kinds of costs: development, production; and support. Empirical evidence suggests that, statistically, production and support costs are positively correlated, but that development effort can be applied to reduce either one or the other or the sum of the two.² Because support costs occur in distant years and are neither accounted for by the project manager nor paid

out of current funds, the present management emphasis is on holding down just the total of development and production costs, even though lifetime support costs may dominate. Methods to internalize the sum of unit acquisition and support costs to a single responsible party are needed if that sum is to be reduced.

Electronics-X has concentrated on five major, high-impact areas. Recommendations in each of those areas are presented in capsule form below:

1. Data Collection and Feedback.^{*} A valid cost and reliability data base by electronic subsystem is needed now--not ten years hence. An interim sampled-data collection procedure for field reliability and marginal maintenance costs is recommended that will provide valid input data and rapid feedback to manufacturers and to producer commands on selected subsystems. The more gradual introduction of a complete and uniform cost accounting system is also recommended.
2. Requirements.^{**} Modification and extension of structured management reviews are recommended to help uncover the real minimum needs and to avoid hidden but costly risks. Performance, physical characteristics, cost, quantity, and schedule need to be specified in the initial requirements statement, and tradeoffs should be carried on throughout the acquisition cycle--all with a realistic but not immutable perception of the real threat or need.
3. Competition and Management Options.^{***} Policies and practices are outlined with the potential to greatly increase the freedom of action and the alternatives available to DOD at

^{*} For findings and recommendations in greater detail, see Sections I-B-1 and I-B-2.

^{**} For findings and recommendations in greater detail, see Section I-B-3.

^{***} For findings and recommendations in greater detail, see Sections I-B-6, I-B-7, I-B-11, I-B-12, and I-B-14.

every point throughout the acquisition and maintenance cycle. The groundwork must be carefully laid to develop competitive production sources of equipment and sources of maintenance services. For many types of electronic equipment, this entails standardizing interfaces to ensure interchangeability of competing designs, preference for "what to do" specifications over "how to do" specifications, avoiding lock-in to a single supplier, allowing technological evolution within the constraints of interface specifications, and providing alternatives to the current preponderance of military maintenance and repair activity in the many cases where combat effectiveness is not really enhanced by military maintenance.

4. Reliability Enhancement.^{*} The key to reliability is simplicity; purging requirements and specifications of questionable or unnecessary design demands will simultaneously reduce acquisition costs and support requirements. Quantitative reliability requirements can and should be made realizable and consistent with expected equipment complexity and should then be achieved through formal factory and field programs aimed at reliability growth. Transferring the maintenance burden to suppliers through the use of long-term warranties, where feasible, can be expected to motivate supplier effort toward evolving increasingly reliable and maintainable equipment designs and toward minimizing the sum of the production and support costs.
5. Maintenance Training.^{**} A reversal of current maintenance training sequences is recommended to make earlier and more efficient use of the scarce military manpower in this era of the volunteer force. This entails teaching green maintenance

^{*} For findings and recommendations in greater detail, see Sections I-B-5, I-B-9, and I-B-11.

^{**} For findings and recommendations in greater detail, see Section I-B-10.

personnel to do useful work by making use of job performance aids (JPAs) before leading them into engineering fundamentals. The approach is expected to make new maintenance personnel more productive during their initial enlistments.

Individual findings and recommendations are presented in more detail in Section I-B following. More extended analysis, discussion, and backup can be found in the complete report.

The term "electronics" covers a broad array of devices, equipment, subsystems and systems. Therefore, we have attempted to indicate in the ensuing recommendations, where possible, the specific classes of electronics to which they evidently apply. This gives rise to the risk that certain concepts that we believe to be important may be interpreted too narrowly. Specifically:

- The theme of encouraging and sustaining both design and price competition through production, we assert, applies to many large systems as well as to small equipments and should be considered as a possibility in every case, although for large systems specific analyses of alternatives will be required to arrive at the best course of action.
- The theme of substituting unit replacement for unit repair at organizational maintenance levels and getting factory repair through long-term supplier warranties as an alternative to military repair, we suggest, has applicability wherever the transportation facilities will permit, and the U.S. military is generally well supported with transportation. In any event, electronic unit replacement will not impose a significantly greater overall burden on transportation than will field repair. Furthermore, analysis on a military-mission basis can be used to determine appropriate tradeoffs in place of the past a priori assumption that in most cases field repair is both necessary and desirable.
- The concept of encouraging evolution of internal design and modifications to enhance reliability within the constraints

of interface standards, we well realize, opposes the conventional wisdom that spares stocking and military repair will become burdensome if internal configurations are not firmly fixed, but we believe that exaggerated concern with internal configuration control before achieving reliability objectives has in a good many cases exacerbated rather than relieved the maintenance burden. However, rigorous configuration control at standardized interfaces is clearly essential.

B. FINDINGS AND RECOMMENDATIONS

1. Cost Data Collection and Reporting Systems

Finding:

Throughout the Electronics-X Study, we have encountered a profound lack of valid cost data and overwhelming inadequacies in the pertinent reporting systems. More specifically:

- DOD appears to have no cost accounting system capable of providing data on the full life-cycle costs of any electronic subsystem. Full life-cycle costs include RDT&E, Procurement, O&M, Military Personnel costs, other direct costs, allocable indirect costs, and depreciation or other measure of capital investment in support equipment and facilities. Maintenance costs and indirect costs, in particular, are very inadequately known from a cost accounting point of view. Moreover, there is often confusion as to the significance of the various reported costs because of inadequate or nonuniform definition of cost elements. As a result, cost estimation and cost-effectiveness tradeoffs are difficult at best and often impossible.⁵

Recommendations:

- ★★★ A systematic effort should be undertaken to develop a step-wise implementation of a complete and uniform cost accounting system throughout DOD, with emphasis on valid input

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data. This system must be compatible with the cost accounting system for DOD contractors that is evolving under the aegis of the Cost Accounting Standards Board. It must allow meaningful comparison between Service in-house costs and contractor costs on individual systems, subsystems, and equipments. As a first step, a marginal cost system using sampling techniques for support-cost inputs should be implemented. The system must then evolve to cover full costs of both acquisition and support.

- ★★ A central organization within OSD should be designated to organize this cost information system and to coordinate the efforts of responsible Service elements.
- ★ To test and exercise the system, each Service major procurement command should designate certain electronic systems for review of cost reporting requirements. Appropriate steps should be taken to ensure consistency among the report outputs, complete record retrieval, and periodic validation of the reported costs. These records should be centrally located and should be made available to the cost analysis community.

2. Reliability Data Collection and Reporting Systems

Findings:

- There is no routine field-reliability reporting system in DOD that can provide meaningful feedback to producer commands and to manufacturers on the field reliability of electronic subsystems. Existing maintenance data collection systems were not originally designed for reporting reliability data, and they do not perform this function adequately. Moreover, there is considerable confusion in the terms used to describe reliability. They are first used in specifications in one context and are then employed

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in field reports in another context. The field-use environment and the field-maintenance environment are not adequately quantified in field reports to ensure consistent interpretation of field data. Thus, field information is ambiguous at best. This poses a difficulty in predicting and specifying reliability and in comparing the attained field reliability with the specification.⁴

- There exists one reliability data collection system that appears to be working effectively: TAMMS-SDC, a data-sampling system used by the Army. It utilizes technically trained, experienced field service personnel to sample reliability data and certain other information according to individualized sampling plans. It thus provides a possible model for the rapid, cost-effective implementation of a data collection system for selected equipments.^{4,5}

Recommendations:

- ★★★ In each major producer command (AMC, NMC, AFSC, AFLC), establish (or broaden) a system for competent technical reporting of reliability, availability, and maintainability (RAM) and marginal cost feedback information from the field on selected systems and equipments, using sampling methods. Identify in each such command a data-sampling planning organization to plan and outline in detail the sampled information to be collected and the sampling methods to be used, and designate a suitable data-processing activity to process and distribute the outputs of the data-sampling system.

Prime candidates for sample data collection are:

- Newly deployed systems during the first year of operation
- Systems/subsystems deployed in large quantity
- Subsystems/equipments critical for the operation of major systems or being procured as GFE for major systems.

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★★ Organize a RAM Data Systems Task Force, representing the several Services and chaired by OSD, to study and compare the relative cost-effectiveness of a routine maintenance data collection system (such as 3M or AFM 66-1) with a sampled-data collection system (such as TAMMS-SDC). Consider and recommend the advisability of possible courses of action such as the following:

1. Discontinue routine processing of TAMMS-Aviation, 3M, and AFM-66-1 RAM data at the national level. Replace these systems by sampled-data collection systems.
2. Continue processing at the national level all safety-related RAM information, such as 3M-Aviation, AFM 66-1, and TAMMS-Aviation. Supplement these systems by periodic sampling studies to check and improve the information collected by the maintenance data collection systems.
3. Extend the maintenance data collection systems to the depot level in selected cases and ensure that all cost information and RAM information is compatible in format (Single-Thread Data System) so that it can be aggregated by system.

★ Establish a new RAM Information Exchange Program at the electronic equipment level in a form patterned after the Government-Industry Data Exchange Program (GIDEP). It should

- Provide automatic interchange of RAM data related to parts, components, equipments, subsystems, and systems utilized by the Services.
- Have participants from Army, Navy, Air Force, NASA, Canadian Military Electronics Standards Agency (CAMESA), and numerous contractors.
- Be chartered by Joint Logistics Commanders.

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- Provide a forum for an organized direct exchange of this information with other Services and with all interested contractors.

3. Requirements and Acquisition Decisions

Findings:

- A requirement for a system or subsystem may be defined as including performance, physical characteristics, cost, quantity, and schedule--all in conformity with a statement of threat or need. While the overall requirements and acquisition decision process includes attention to all these components, the current approach to establishing a requirement tends to start with desired performance and characteristics. Cost, quantity, and schedule are modifiers, added later. Thus, requirements tend to be performance-driven, with inadequate early consideration of pragmatic essentials.⁶
- The requirements and acquisition decision process includes, at least formally, the attributes necessary for effective management of system acquisition. In actual implementation, however, cost-driving aberrations of the process occur at several stages: in establishing the original requirement and in expanding it into system characteristics and specifications; in the interactions between management practices and advanced technology; in cost estimating; and in contracting practices.⁶
- Costs of progressions of wholly new-generation weapons systems have increased much faster than costs of progressions of product-improved systems, even when the product improvements have involved incorporation of new generations of electronic subsystems. This suggests that cost savings would result if, in establishing requirements, within-generation system improvements were favored over totally new-generation developments, where that is feasible within the uncertainties of threat or need. The additional costs

of new-generation systems appear to arise partly from trying to drive new vehicle, engine, and electronics developments all to the same schedule, and partly from the engineering difficulties in achieving compatibility among all three when none of them is yet defined well enough to permit prediction of the interactions when they are combined. This suggests that cost savings could be achieved if electronics IOCs were established separately and independently of vehicle IOCs, when feasible, and the electronic subsystems were independently developed. The specification of form, fit (interface), and function requirements for the electronics is essential to such independent development. Independent development would make possible the consolidation of requirements for like electronic subsystems and equipment and would broaden the applicability of specific designs to several systems.⁶

- Other important aberrations of the requirements process leading to cost growth include: selection of desired operating points too high on the cost-performance curve; failure to allow for uncertainty in selecting the operating point; cascading of detailed requirements between the decision and detailed implementation levels; and failure to iterate requirements decisions as development experience is gained.⁶
- There is insufficient visibility, at top management levels, of potentially cost-driving electronic subsystem problems.⁶

Recommendations:

- ★★★ In exploring and establishing a system requirement, give performance, physical characteristics, cost, quantity, and schedule equal status from the beginning, and perform trade-offs among these early in the game.
- ★★★ In major system developments, separate vehicle IOCs and electronic subsystem IOCs where possible, and develop the

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electronics independently. Consolidate like subsystem or equipment requirements wherever feasible.

- ★★★ Increase visibility to top-level management of potentially cost-driving developments of electronic subsystems associated with major systems by instituting suitable review prior to each DSARC review. As appropriate, provide for a similar visibility to management of developments of less-than-major electronic subsystems and equipments by refocusing reviews to make them analogous to DSARC reviews, but at lower management levels.
- ★★★ Give increased consideration to product-improvement programs as a means of fulfilling new requirements, as opposed to institution of wholly new development programs.
- ★★★ Select technology and performance objectives for new developments conservatively (i.e., low on the cost-performance curve), except in cases where military necessity imposes an overriding need for risk-taking to achieve extremes of performance. Allow for uncertainty in establishing the corresponding system requirements.
- ★★★ Iterate requirement and acquisition decisions if performance, characteristics, cost, quantity, or schedule departs significantly from initial plans during development. Establish criteria to trigger such iteration.

4. Design to Cost

Findings:

- Design to cost (DTC) in defense systems acquisition is still in its infancy. Among the problems yet to be solved are:
 - How to establish the cost target in view of the lack of an adequate data base and limited cost-estimating techniques.

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- How to resolve the uncertainty for the user resulting from continual cost-performance tradeoffs and their potential effects on force size, capability, and logistics.
 - How to incorporate commercial cost-saving practices in DOD DTC procedures when motivations and accountability are basically different in the two sectors.
 - And how to extend competition through the acquisition cycle, especially for acquisition of large-scale systems and for large-scale procurements.⁷
- Institutional factors, established ways of doing business, and organizational inertia still lead to DTC procurement practices not consistent with the DTC philosophy, such as: provisions for separate evaluations of the cost and the technical aspects of the proposals, thus precluding the requisite tradeoffs;⁷ requirements for too early and too detailed configuration control that will interfere with evolutionary improvements;⁸ inflexible application of restrictive specifications on materials, parts, processes, and finishes;⁹ and various other restrictive provisions.⁷
 - DTC developments may be more expensive than traditional developments in which production cost is not invoked as a design parameter.¹⁰
 - Wholehearted implementation of DTC in military electronics implies:
 - Greater reliance on proven technology, with technological advance driven largely by the commercial sector in areas of broad commercial usage.
 - Changed logistics procedures, including more detailed analyses and regular consideration of the alternatives of contractor maintenance or of "zero maintenance" (i.e., throwaway parts or components).

- Use of interface standardization and the resultant evolution of several competing interchangeable designs, with consequently increased logistic complexity. Such added logistic complexity can be more tolerable if the aforementioned changes in maintenance concepts are implemented.⁷
- The experimental and other major-system DTC acquisitions initiated in 1972 will not be complete in time to provide DOD the experience needed for other acquisition programs in the near future. DOD will therefore probably have to attempt to act on "lessons learned" before the "experiment" is completed.⁷
- The ASPR includes no barriers to DTC, but some associated contract implementation practices of long standing must be changed to obtain the full flexibility that DTC requires.⁷

Recommendations:

- ★★★ Choose easily defined DTC cost targets such as unit production or flyaway costs (rather than, for example, the presently still ill-defined life-cycle costs; but see next paragraph). Establish such targets early, permitting successive revisions during development, contractual commitment to a unit cost for low-rate initial production (LRIP) at the start of LRIP, and another contractual commitment for unit cost at the start of full-scale production for systems to be procured in quantity. Flexibility to revise cost targets should decrease and should be based increasingly on firm experience as the development-to-production cycle progresses.

If the equipment is to be maintained by the supplier under long-term warranty, the DTC target can be established as the sum of the production cost and total warranty cost; this sum may be considered a surrogate for life-cycle cost.

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But if military maintenance is contemplated, establishing life-cycle cost as a DTC target is not now appropriate because of the inadequacy of current knowledge of the cost to the Government of military maintenance, and of the dependence of these costs on equipment parameters.

- ★★★ Establish explicit limits of deviation from "desired" performance/characteristics/cost/schedule/quantity requirements, and authorize program managers to trade off freely among these separate requirement parameters within the established limits. Establish "desired" parameters and permissible deviations such that tradeoffs are in fact possible and not subject to hidden constraints due to technical feasibility, absolute force requirements, or available budgets.
- ★★★ To the extent feasible, maintain design and price competition throughout the acquisition process, especially for components and subsystems.
- ★★★ In the contractor selection process, ensure that performance and cost are considered together rather than evaluated separately.
- ★★ This study identified only one DTC acquisition, namely, the Navy electronic warfare suite, that uses the approach of specifying equipment needs and requirements functionally, leaving it to the competing contractors to propose optimal development and production strategies to maximize payoff to both the Government and the contractors, and including maintenance strategies among the variables. More experimentation with this approach should be undertaken.
- ★ Increase the number of DTC acquisitions of electronic subsystems designated as "experimental" for observation and extraction of "lessons learned." Include in these observations the electronic subsystems of the 17 major systems designated as "design to cost" in early 1973.¹¹ In further

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experimental DTC acquisitions, seek wider variation of the management variables relevant to DTC (for example, tradeoffs among requirements, program manager's freedom to trade off, competition throughout the acquisition cycle, and different types of contract). The Services should publish "lessons learned" periodically to maximize the pool of explicitly analyzed experience available to all.

- ★★ Review the contracting procedures associated with DTC contracts, modify those that inhibit requisite DTC flexibility, and incorporate the modifications in the ASPR, if necessary.

5. Design for Improved Reliability

Findings:

- The essence of reliability is simplicity. Empirical evidence indicates clearly that most equipments of high unit production cost or high complexity have lower MTBF than equipments of lower unit production cost or lower complexity.¹²
- The reliability of electronic components is improving rapidly, and design revisions to incorporate modern technology at the appropriate stage of maturity can substantially improve electronic equipment reliability without detriment to performance. However, premature or inappropriate application of new technology leads to reduced utility.¹³
- Few military development programs are aimed at increasing reliability through simplification or technological upgrading while holding performance constant.¹³
- Attainable reliability can be crudely predicted on the basis of equipment complexity or unit production cost. Reliability requirements in specifications, however, are not based on such predictions and thus are frequently impossibly high or needlessly low.^{12,13}

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- System partitioning into LRUs or WRAs can be devised in a way that minimizes support costs, if this aspect of system design is considered simultaneously with planned provisioning and maintenance practices.
- The growth of measured reliability is often sluggish in the factory. After the equipment is received by the Services, the field reliability often never achieves growth; rather, it declines. Formal reliability monitoring and management can speed reliability growth both in the factory and in the field and make the ultimate cost and outcome predictable.¹³
- Motivating a contractor to design for minimum life-cycle cost is an important potential stimulant to reliability improvement. One approach is to make the contractor responsible for maintenance as well as production costs through the application of long-term warranties. But complete transfer of an unlimited maintenance risk to the contractor may be impractical, as may be seen by analogy to the failures of the total-package procurement process. It is necessary to devise new ways--possibly new types of warranties--to accomplish this in a pragmatically acceptable manner.^{13,14}

Recommendations:

- ★★★ Limit the complexity of new subsystem or equipment designs (as measured by criteria such as unit production cost or parts count) to a level consistent with the reliability required by a mission analysis. Require evidence of compliance as a preliminary to DSARC review for electronic subsystems of major systems, and as a preliminary to sub-DSARC review for independently developed electronic subsystems.
- ★★★ Require contractually the in-plant use of a formal management methodology, such as methods using Duane-curve monitoring,¹³ to ensure reliability growth in electronic equipments

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and systems. For field-reliability enhancement, a formal reliability-growth management technique should be applied (by Service management action or contractual requirement) to selected equipments on an experimental basis.

- ★★★ Use long-term contractor maintenance warranties to motivate the contractor to design for minimum life-cycle cost. [See the later recommendations on warranties (Section I-B-11) for further details.]
- ★★★ Specify the reliability of electronic equipments or systems to be consistent with predictions based on their anticipated complexity (or unit production cost, as a surrogate for complexity).
- ★★★ Undertake redesign of selected equipments with the specific objective of improving reliability while holding performance constant. The selection of equipments to be redesigned should be based on expected future utility and an observed reliability substantially lower than that predictably realizable by using up-to-date, proven technology.

6. Design to Facilitate Competition

Findings:

- Competition is a missing ingredient in about two-thirds of military prime contract awards. Even when a program does admit development competition, there is a strong tendency for the Government to become locked into a single supplier in subsequent production. The loss of Government freedom of action permits suppliers to force prices up by various devices. The use of large-scale, multiyear buys exacerbates the risks to both the Government and its suppliers, as well as inducing design stagnation in the equipment procured.¹⁵

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- Competition among similar equipments designed by different suppliers and the upgrading of the electronics complement of weapons systems are both now severely inhibited by the lack of interchangeability among like equipments and the consequent high cost and enormous inconvenience of modifying installations to accommodate substitutions.^{9,16}
- In commercial airline electronics and elsewhere in the civilian economy, interface standardization and continuing design and price competition are used to hold prices down, maintain alternative sources of supply, encourage design improvement, and allow for interchangeability among successive generations of electronic subsystems. Periodic buys spaced over the procurement period minimize the impact of buyer or supplier error in any one contract.^{16,17}

Recommendations:

- ★★★ Lay the groundwork for future design and price competition through production and for ready replacement of old designs by new-generation equipment by ensuring the interchangeability of similar equipments intended for similar applications. Accomplish this by including (or by requiring prime contractors to include) mechanical, electrical, and environmental interface standards for each unit as a part of military electronic equipment specifications.

Require design interchangeability when production competition or design upgrading is foreseen as desirable or likely. Equipment classes that, by virtue of large dollar volume or rapid technological growth, are judged ripe for initial application of interface standardization are: airborne communication, navigation, identification and weather radar equipments; vehicular communication equipments; and modular electronics packages for tactical missiles.

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- ★★★ Modify approval processes for engineering-change proposals to expedite incorporation by suppliers of internal design improvements to enhance reliability and performance or inclusion of new technology to meet competition during the procurement cycle and even after deployment, if the suppliers are called upon to maintain their equipment. But keep rigid control over interface configurations to ensure interchangeability.
- ★★★ Obtain multiple developments of equipments conforming to interface specifications. Where the potential market for the equipment is large enough, encourage industry-financed development; otherwise, procure multiple developments under Government contracts.
- ★★★ Facilitate Government testing and qualification of designs offered in compliance with the specifications, whether or not the designs were developed under Government contract. Plan, prepare, and provide for retesting and requalification of modified designs submitted in production competitions subsequent to the initial competition.
- ★★★ To overcome the potential problem of spare-parts stocking and field repair of multiple equipment configurations, make use of depot repair or supplier maintenance under warranty. In the field, replace rather than repair failed replaceable units of equipment. Include warranty requirements when initiating development.
- ★★ To achieve multiple-source availability, rely on performance specifications plus environmental and interface requirements (i.e., "form, fit, function" specifications) to define equipment, rather than imposing detailed specifications on parts, processes, materials, and internal configuration.

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- ★ To broaden the markets for competitive suppliers, encourage the evolution of multi-Service interface standards.

7. Production

The following broadly stated findings and recommendations apply in such a surprisingly large variety of situations that we have chosen to state them without detailed recitation of numerous and important exceptions in order that their potential applicability be studied in every case. Yet their validity clearly varies, depending on the class of electronics involved. In general terms, they are rarely valid for the one-of-a-kind, not-too-high-priced item. They are almost always true for large-number, high-dollar production contracts. In between, their validity varies, and the applicability of these recommendations should be studied carefully, not dismissed a priori. An important consideration, for example, is unit development cost versus unit production cost. Another is the required degree of integration of the subsystem with the overall system.

Findings:

- Production-price competition generally reduces the cost of military electronics. The cost reductions resulting from competition often substantially exceed those realizable by extending the price-quantity projections ("learning curves") of the original suppliers.¹⁸
- Aggregating requirements into a single, large, multiyear procurement not only precludes the cost reductions obtainable from competition but also makes the Government vulnerable to upward price pressures by the selected supplier and induces design stagnation.¹⁹
- The potential benefit of competition in reducing production costs is larger in high-dollar-value items and large contracts than in smaller ones, but is seldom pursued because

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of inhibitions against incurring the additional front-end costs associated with establishing a second source.^{18,20}

- Production competition may be expected to cut a substantial amount, such as 20 percent, from total production costs. The potential savings are often more than adequate to completely finance a competitive development, depending on the ratio of development costs to production costs and on the period over which planned procurements are to take place. That period is often determined by factors such as budget limits and the need for maintaining the defense industrial base rather than by optimum production scheduling; however, the high cost of accomplishing these other objectives should be reconsidered.^{19,20}
- Where feasible, carrying on design competition as well as price competition through production will encourage a succession of technological improvements to the product that will mitigate the pressures for drastic design changes.^{19,20}
- Sustaining design competition through production requires Government procurement strategies that differ from those of the traditional competition for production of a single selected design. Losers of an initial competition must be offered inducements to continue upgrading their designs, and potential new competitors must be offered inducements to develop competing designs. The development effort required may impose substantial financial risks on the developers. To encourage the taking of such risks, the Government must be able to provide credible assurance that such risk-taking has reasonable expectation of realizing rewards by winning future competitions. A concerted effort should be made to identify systems, subsystems, and components to which this approach is applicable.^{16,17,19}

Recommendations:

- ★★★ Where the quantity to be bought is large enough, depart from the conventional approach of aggregating procurements into a single large buy intended to take advantage of "learning curves." Instead, fragment the procurements into sequential buys, inviting design and price competition on each buy by the several suppliers of qualified interchangeable equipments.
- ★★ The Government must assure prospective suppliers that there will be future design and price competition. One method of so doing is to analyze and publish future needs and a schedule of planned competitive buys.
- ★★★ The Government must provide assurance that new or improved designs will be given full consideration in future competitions if they meet the form, fit, and function requirements that ensure interchangeability with prior designs. This implies the need for inclusion of interface requirements in Government specifications.
- ★★★ The Government must offer to perform and must be prepared to perform laboratory tests and evaluations of the actual hardware prototypes offered by bidders or prospective competitors in order to qualify the designs for current and future competition.
- ★ When it is desirable and necessary to sustain competition, award fractions of each buy to two or three competitors in proportion to the merit of their respective designs and prices, rather than making the award on a winner-take-all basis.

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8. Reprocurement

Finding:

- Where a single design must be procured and later reprocured, experience has shown that dependence upon reprocurement data packages to enable a second source to reproduce the design has often resulted in failure because the original reprocurement data package cannot convey all the information required for successful production of the design. On the other hand, there is abundant commercial experience with successful licensing and second-sourcing, which occurs when the original vendor believes that having an effective second source is essential to his own profitability. In such cases, the vendor conveys the information not just via a data package but also via actual people-to-people contact.²¹

Recommendation:

- ★★ In selected development contracts where subsequent competitive reprocurement is anticipated, the Government should provide a payment to the developer for each accepted unit produced under Government contract from the developer's design by a supplier other than the developer. This payment should constitute a deferred part of the compensation for the reprocurement data package. Such a contracting procedure should be used by the Government on a trial basis.

9. Maintenance

Findings:

- Annual DOD expenditures for electronics maintenance are estimated to approximate those for production procurement (more than \$5 billion).²²
- As indicated in prior findings, electronics maintenance cost visibility is needed before management action to reduce cost

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can be maximally effective. DOD cost reporting systems do not now provide this visibility.

- While there is competition in the procurement process, competition among maintenance sources is rarely used as an inducement to reducing costs. Only a small fraction (about 8 percent) of the maintenance effort is contracted, while more than 90 percent is performed by military maintenance personnel and activities.²²
- The DOD policy guideline that at least 30 percent of mission-essential depot maintenance be done on contract is not being followed in electronics by the Army and Navy. The Army contracts out about 7 percent and the Navy 16 percent. (The Air Force figure is 35 percent.)²³
- Because of increased pay rates and increased turnover, training, and support costs, maintenance by uniformed personnel is likely to be more expensive than maintenance by contractors or Civil Service, although the lack of good cost data masks the issue.²³
- The provision of maintenance billets at U.S. bases to accommodate rotation of military personnel from overseas complicates the use of civilianization as a cost-reducing technique. Such rotation billets should be carefully identified as a cost element other than maintenance so that their cost can be properly ascribed.²³
- The present accounting system does not allow a clear separation of true maintenance costs from costs of nonmaintenance functions performed by military personnel occupying maintenance billets. Nor does the system allow a cost comparison between military and contractor maintenance or between two different military facilities.²³

Recommendations:

- ★★★ As recommended earlier, institute a cost accounting system that will afford visibility of the maintenance process and make possible realistic cost comparisons between military and industrial maintenance. Implementation in all the Services of the Uniform Depot Maintenance Cost Accounting and Production Reporting System (OSD Instruction 7220.29) would be an important part of such a system.
- ★★ Provide separate accounts for functions other than maintenance, such as the use of U.S. maintenance billets to facilitate the rotation of military personnel not involved in maintenance, or for personnel in training.
- ★★★ Establish alternative sources of maintenance, including the maximum feasible amount of contractor maintenance, to foster competition and resultant efficiency in the maintenance process and to ensure the proper utilization of scarce military personnel in the present zero-draft environment.
- ★★ Intensify efforts to reduce field maintenance by shifting complex tasks from the organizational and intermediate levels to the depots, taking due account of increased turnaround time and transportation problems.

10. Maintenance Training

Findings:

- There is high turnover among electronics maintenance personnel. The training period is long, and personnel seldom become productive until the end of the initial enlistment period. The median level of experience is less than 3 years. These factors result in an expensive and unproductive maintenance force, high training cost (averaging \$3000-\$10,000 per man-year), and high turnover.²³

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- A training sequence in which a trainee first learns to perform maintenance tasks on specific equipments and defers learning general theory gives him early capability to do productive work and prepares him for later advanced study. This training sequence is the reverse of the current process.²⁴
- Successful, speedy, and accurate performance of maintenance tasks by green technicians can be made possible by the use of fully proceduralized job performance aids.²⁴

Recommendations:

- ★★★ Develop fully proceduralized job performance aids for use in routine maintenance of new weapons systems and for selected tasks in high-maintenance portions of existing systems.
- ★★★ Selectively, on a trial basis, reorient the training sequence for electronic technicians so as to provide first the specific training they require to perform maintenance tasks by using proceduralized aids during their initial enlistments.
- ★ Increase research on job performance aids and on job-oriented training to enable the utilization of personnel of lower ability levels and to enhance learning on the job. Apply the results in selected training programs.

11. Warranties

Findings:

- Long-term contractor maintenance warranties provide a technique by which both production and maintenance costs can be internalized to a single responsible organization: the supplier.²⁵

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- Making the supplier-warrantor responsible for both production and long-term maintenance costs under fixed-price contracts will strongly motivate him to design equipment so as to reduce the sum of these costs, which constitute a major fraction of the life-cycle cost.²⁵
- The limited experience with long-term contractor maintenance warranties to date suggests that they in fact motivate designs and modifications to increase reliability, and that the cost of contractor maintenance through warranties is substantially less than just the direct costs of military maintenance on comparable items.²⁵
- Short-term warranties on materials and workmanship have been extensively invoked in the past in military electronics procurements, but such warranties have been ineffectual and are not comparable to long-term contractor maintenance warranties.²⁵
- The use of long-term contractor maintenance warranties can serve as a competitive alternative to military repair of electronic equipment.^{23,25}
- Long-term contractor maintenance warranties have application to any military electronic equipment whose failed units can be replaced in the field and conveniently returned to the contractor for repair, or to which the contractor can have ready access for field repair.²⁵
- The costs of warranty maintenance should take into account the cost of any additional spare replacement units required, the costs of transportation for repair, and the warranty costs themselves. These costs should be compared with the costs of the spare components and the logistic system required to supply them to the field, plus the true direct and indirect costs of military maintenance.²⁵

- Post-warranty maintenance options include warranty renewal, maintenance contracts, or contractor training of military maintenance personnel. Any of these options would alleviate the need for excessively detailed data and manuals.²¹
- Trial application of long-term contract maintenance warranties was requested of the Services by DDR&E and ASD(I&L) in a joint memorandum of 27 August 1973.

Recommendations:

- ★★★ Extend the application of long-term contractor maintenance warranties to military electronics procurements.
- ★★★ Make known the intention to contract for maintenance warranties on production equipment at the time development is initiated, so that the contractor will design to minimize total costs of production and warranty maintenance.
- ★★★ Establish a warranty review group within OSD to monitor results of trial applications, to determine desirable warranty contractual formats, and to refine the categories of equipments to which warranties are most applicable and for which warranties are most effective.
- ★★★ Initially, apply long-term contractor maintenance warranties to equipments whose failed units can be replaced in the field and conveniently returned to the contractor's plant or base for repair, or to which the contractor can have ready access for field repair, such as: airborne communication, navigation, and identification equipment; modular radars; vehicular communication sets; complex manpack equipment such as LORAN C/D; forward-looking infrared (FLIR) systems; and domestic communication, data processing, and radar installations.

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12. Design Evolution and Configuration Management

Findings:

- A new DOD regulation, "Configuration Management," is in the last stages of signoff prior to official promulgation. It will establish policies and practices applicable to all segments of DOD. As it now stands, this draft regulation still has the following drawbacks:⁸
 1. It unduly restricts the freedom required by a supplier-warrantor to make the evolutionary internal design changes he sees as needed to increase reliability and thus to decrease the sum of unit production cost plus unit contractor maintenance warranty cost.
 2. It imposes a configuration baseline at the end of full-scale development. Thus, all changes after this point--and experience shows there are many--must undergo the formal configuration-change processing routine, a routine that has often led to delays in the past despite good intentions and reasonable procedures.
 3. Its effect would be to restrict the freedom required to make tradeoffs between cost, performance, schedule, and quantity in design-to-cost contracts.
- The draft regulation properly emphasizes the requirements for meticulous configuration-status accounting and keeping technical documentation current with the configuration.⁸

Recommendations:

- ★★★ The about-to-be-promulgated DOD regulation on configuration management should be adopted with the following modifications:
1. It should specifically permit consideration of changes that are of benefit to the contractor and not detrimental to the Government.

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2. It should establish two product baselines, the first a "tentative" one at the end of full-scale development, and the second, "final" one when the design has been adequately stabilized (see below).
3. It should permit internal equipment changes that do not affect form, fit (compatibility and interfaces), function, price, or delivery to be classified Class II (as defined in the regulation) in order to facilitate the change approval process until the "final" product baseline is invoked by the Government.

★★★ The Government should defer invocation of the final product baseline, as applicable to electronic equipment, until field reliability objectives have been achieved, or, in the case of equipment under contract maintenance warranty, until the warranty period is about to end and the Government is about to take over maintenance from the warrantor.

★★★ The Government should defer full spares stocking until after the final product baseline is invoked.

13. Project Management

Finding:

- Design to cost is a concept which depends for its success on the flexibility and timeliness of management decisions. Such decisions are usually best made at the project-manager level, provided that the project manager has the requisite authority--for example, sufficient authority to shift funds from one program to another in a multiprogram project office, and thus to defer or eliminate lower priority tasks in one program in order to expedite high-priority tasks in another program. This reprogramming authority is present in

★★★ Highest priority; ★★ high priority; ★ priority.

some multiprogram offices but is absent in others, largely because different line items in the budget are often controlled by different "sponsors" in the headquarters organization, and each sponsor guards his share of the budget.²⁶

Recommendations:

- ★★★ Use the multiprogram project office ("basket" SPO) structure for all independent electronic subsystem development where a number of related or similar developments can be grouped under one perpetual project manager (PM) to provide a PM of higher rank and greater authority, better project office personnel, more responsive support from functional groups, and more tradeoff flexibility.
- ★★★ Provide multiprogram project offices with sufficient flexibility in the use of available R&D funds to allow the necessary tradeoffs by the PM in the development, OT&E, and LRIP phases.
- ★★ Arrange for the project manager or prospective project manager to participate in drafting the operational requirements before developing specifications for subsystems under his jurisdiction.
- ★★ Make available to system project managers catalogs of available electronic equipment that show current price and reliability figures as well as technical descriptions.

14. Standardization and Specifications

Findings:

- In the rapidly moving technology of military electronics, the standardization that occurs because of repeated procurements of the same design can result in technological stagnation, mediocre reliability, and excessive proliferation

★★★ Highest priority; ★★ high priority; ★ priority.

of alternative equipments. This has been exemplified by the AN/ARC-34 UHF radio set and the AN/ARN-21 TACAN.²⁷

- By way of contrast, interface standardization at the black box, LRU, or WRA level provides a practical form of standardization which has been shown to work both in the civilian airline industry and in military mission-oriented equipment, such as the Navy's Standard Missile. As used by the airline industry, the interface standardization approach is combined with functional specifications, that is, "form, fit, function" standardization. This has the advantage that while the interface is standardized, the internal configuration of the unit can evolve as technology changes, taking advantage of new devices and new materials. Interface standardization can be used in conjunction with military standards for components and workmanship. Limitations on the evolution inside the unit result, but these specifications provide a degree of insurance against the mistakes of an incompetent or greedy vendor. In either case, technological progress is not halted by standardization. Moreover, interchangeability between old and new generations of electronics becomes a practical reality, and the need for modifications to an installation to accommodate the new equipment is eliminated. With interface standardization, production costs can be held down by competition among interchangeable designs, and new systems can be synthesized largely from proven standard units.²⁷
- Strict military environmental requirements imposed on equipment and systems cause great increases in cost. The provision of more benign standard environments for electronic equipments through control of humidity and temperature and isolation from shock and vibration would make possible the use of cheaper and more readily available devices.²⁷

- In an area as dynamic as electronic technology, the vast DOD system of military standards and specifications is too sluggish to follow the rapid advances in technology. But by providing instructive guidelines for the uninitiated, it does have the valuable function of admitting novices in military electronics design and manufacture to the competition for development and production of hardware.²⁷
- Integrated-circuit development is being driven by commercial rather than military demand, and the production prices of such items produced in commercial volume are very low. Military equipment developers should make use of the existing library of commercial MSI and LSI components where feasible, rather than entering into uniquely military integrated-circuit developments; and dependence on a single source for such components should be avoided wherever possible.²⁸
- The impact of standardization and specifications on electronics cost is of such large magnitude that establishing electronics standardization and specification policy should be undertaken in the Office of the Secretary of Defense.²⁷

Recommendations:

- ★★★ DOD should establish an Electronic Standards Panel having responsibility and authority to
 - ★★★ 1. Promulgate policy requiring that the Services include electrical, mechanical, and environmental interface specifications in specifications for electronic equipment.
 - ★★ 2. Promulgate policy requiring that the Services take steps toward assuring that new electronic equipments that are likely to replace older equipments in aircraft, ground vehicles, and other platforms

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will be made electrically, mechanically, and environmentally interchangeable with the older equipments, of similar types, so that the new equipments can be substituted for the old without costly installation modification.

- ★★★ 3. Promulgate policy requiring that equipments, subsystems, or systems of similar types be developed to the same interface specifications, so that they may be interchanged.
- ★★ 4. Promulgate specific interface standards for classes of equipment used by more than one Service.
- ★★ 5. Establish and promulgate standards for the thermal, atmospheric, vibration, shock, mounting, shielding, and power-source environments to be provided by aircraft, ships, and vehicles in which electronics is to be installed. This should include standards for benign-environment enclosures wherever they are feasible and cost-effective.
- ★★ 6. With the concurrence of and to the extent authorized by the Military Communications Electronics Board, establish and promulgate standards for the signals to be transmitted or interchanged in cooperative systems, such as communications, navigation, and identification systems.
- ★★ 7. Review Service forecasts of electronic equipment needs in order to determine those types and classes to which uniform standards should be applied, and act to ensure that they are applied.
- ★★★ 8. Establish and promulgate DOD standards for the multiplexing and interchange of digital data among electronic equipments within ships and aircraft.

★★★ Highest priority; ★★ high priority; ★ priority.

★★ 9. Promulgate policy designed to ensure maximum compatibility of military standards with commercial practices.

★★ 10. Review existing standards and specifications for parts, materials, finishes, processes, and other aspects of the internal design of military electronics to determine which of these should be

a. Strictly enforced

b. Subject to the substitution of the contractor-validated alternative

c. Regarded as advisory only

d. Revoked.

The several general design specifications used in most electronics procurements (e.g., MIL-E-16400, MIL-E-5400, MIL-I-983) should receive particular early attention.

★★ 11. Issue up-to-date guidance on military utilization of standard commercial LSI and MSI items, with particular attention to the need for multiple sources and avoidance of military-unique designs.

★★ DOD Directive 4120.3 can be the vehicle for the establishment of an effective electronic standards organization. In order to accomplish this, the Defense Materiel Specifications and Standards Board should, under paragraph VII B2 of the Directive, recommend the establishment of an Electronic Standards Panel (ESP), with the authority and responsibility to promulgate multi-Service electronic standards and promote the cause of standardization of electronic equipments, subsystems, and systems, both single-Service and multi-Service. The ESP should be given the further authority to establish continuing (as opposed to ad hoc) committees, to which may be

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delegated segments of the authority and responsibility of the ESP. Once established, the ESP should organize to undertake formulation and promulgation of the policies recommended above.

15. Software

Findings:

- Software costs have exceeded hardware costs by large factors in some military systems using general-purpose computers. Boehm, of the Rand Corporation, reported that the Air Force in 1972 expended between \$1 billion and \$1.5 billion on software (that is, computer programs and associated documentation)--more than twice its expenditures on computer hardware.²⁹
- Software developments are frequently behind schedule, causing other costs to spiral.²⁹
- Software "unreliability" is a euphemism for software errors.²⁹
- The complexity and extent of the software may well be a measure of the mismatch between the hardware and the problem; conversely, by properly designing and structuring the processor, the software problem can be mitigated.²⁹
- The major sources of excessive software costs in conventional systems employing central uniprocessors are the following:²⁹
 1. Selecting hardware and starting programming before the system is designed in detail--that is, before the system functions, organization, inputs, outputs, and transfer functions are thoroughly defined. The flexibility of the digital computer is used as an excuse to procrastinate in system design.

2. Overburdening the central processor with tasks that can be accomplished by specialized peripherals.
3. Selecting too small a central processor, with consequent overutilization of the computer and resort to bad programming practices.
4. Program overintegration, which makes changes difficult.
5. Lack of adequate discipline in software development.
6. Developing a new high-level programming language for every job.
7. Starting programming before the computer design is complete.

Recommendations:

To reduce costs of software in processors employing conventional general-purpose machines, our recommendations are:

- *** Complete the design of the system and the basic program structure in substantial detail before making major commitments to hardware or coding.
- ** Limit the aggregation of problems to be solved on a central machine; as an alternative, decentralize processing by providing peripheral special-purpose devices (either analog or digital) or separate peripheral general-purpose machines to perform specific separable functions.
- ** Select a processor of adequate size to permit underutilizing the computer; write highly modular programs; emphasize structure and overall efficiency rather than hardware efficiency alone.
- ** Use rigorous discipline in software development, such as the top-down Structured-Programming approach.²⁹

*** Highest priority; ** high priority; * priority.

- ★★ Use a standard well-established programming language with which programmers are thoroughly familiar. Use the highest level language appropriate to the task at hand, but avoid the unnecessary development of a unique language.
- ★★ Defer coding until the computer design is substantially complete and firm, except for that necessary to verify hardware-software design compatibility.

16. Digital System Architecture

Findings:

- No current basis exists for the common assumption that conventional centralized programmable uniprocessors are the most effective or most economical bases on which to structure military tactical data systems.²⁹
- The cost of programming is escalating, while the cost of standard computing hardware is plummeting; a new look is needed at the balance between hardware and software in system architecture.²⁹
- The advent of large-scale integration has led to the cheap and plentiful implementation in hardware, on single chips, of standardized complex algorithms together with memory. With hardware implementation of a complex algorithm, the need for writing the algorithm in software is eliminated.²⁹
- There is a growing library of these hardware-implemented, standard, complex computing functions that makes possible the synthesis of specialized processing units and the elimination of much of the software. The low cost and small size of these units mitigate the need for time-sharing their use, and permit distributed processing, federated architectures, associative array processing, and processing structures specifically tailored to system functions.²⁹

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Recommendations:

The principal need in data-processing system design is a reversion to the engineer's approach of first analyzing the problem, then laying out alternate solutions, and then choosing and pursuing the most effective and economical. Specifically,

- ★★★ System-function-oriented processing-hardware structures should be considered as alternatives to the conventional centralized programmable uniprocessor for use in military tactical systems.
- ★★★ The military processing problem should be clearly stated; the system design should be spelled out in detail; and alternate processor architectures and designs should be compared before a hardware approach is selected.
- ★★★ A processor design for each system should be selected and developed that will minimize the combined costs of hardware and software; the allocation of functions between hardware, software, and human operators should be consciously worked out prior to decision.
- ★★ Standard LSI processing elements available from more than one source should be used to the maximum extent possible; development of uniquely military LSI elements should be minimized.
- ★★ Military laboratories should be encouraged to investigate and develop processor architectures, including federated architectures, that fit military problems and are cost-effective. Conversely, their extensive efforts in the programming of conventional uniprocessors should be reduced to bring the overall program into better balance.
- ★★ Commercially successful processors for which software already exists should be considered for DOD applications wherever appropriate.

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- ★★ Formats and speeds for data interchange among sensors, actuators, processors, controls, and displays should be standardized across service lines and for as wide a variety of applications as practicable.

17. Data Costs

Findings:

- The cost of electronics technical data to DOD is very large. It consists of the following: an estimated annual \$600 million formally charged for data; hidden costs charged under the headings of "engineering" or other categories of direct labor; and Government costs entailed in requesting, receiving, reviewing, handling, or storing technical data. On the average, the formal cost of data averages about 10 percent of RDT&E contract costs and 5 percent of production costs.³⁰
- The largest cost items are handbooks and technical manuals, which comprise some 35-50 percent of the total data costs for electronics.³⁰
- The data requirements are so massive that it is impossible for Government personnel to review the submitted material or to test its validity.³⁰
- Discussions with industry representatives show that the re-procurement data submitted in response to contract requirements are not the data used for actual manufacture in the contractor's plant; the plant may use numerical control tapes, while the Government data may consist of exquisite india ink drawings on mylar.³⁰
- The submission of the data is often required too early to be valid. For example, handbooks and provisioning documents may have to be submitted before the equipment design is stabilized.
- Many of the data items required overlap.³⁰

In addition to these observations on the current course of events, it is pertinent to note that, were certain of the recommendations of other sections of this report to be followed, some conventional data requirements would be reduced or eliminated.

1. Were competitive equipments available from two or more suppliers, the need for reprourement data would be eliminated.
2. If direct transfer of information from developer to second-source supplier were encouraged by suitable incentives, the reprourement data package could be reduced in extent and less rigid in format.
3. If equipments were repaired by contractors under warranty or by specialists at depots, the extensive and explicit instructional documentation required for organizational repair by technicians of limited capability could be reduced, and good commercial-grade handbooks would suffice.
4. If competitive prototyping and test were the bases for acceptance of equipment designs, the need for voluminous in-process validation data would be reduced.

Recommendations:

- ★ Accept contractor's data format unless there is a demonstrable advantage in specifying a Government format.
- ★★ Defer the ordering and delivery of contractor data until the need is firmly established.
- ★★ Delay procurement of spares provisioning, technical manuals and maintenance handbooks until the point of design stabilization is identified and reached.
- ★★ Scrub data requirements mercilessly through the efforts of Data Requirements Review Boards that include representation of the project manager, the user, and industry.

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- ★ Where the equipment future is uncertain, buy options on reprourement data instead of the data itself.

The following recommendations, previously made in other contexts, have been recast below to reflect their impact on data costs where applicable.

- Use competing suppliers of interchangeable equipment to reduce the need for reprourement data.
- Use contractor warranties and maintenance to reduce the need for technical and maintenance manuals and provisioning data.
- Rely on competitive prototyping and test as a substitute for voluminous in-process validation data (and as a substitute for myriad detailed specifications).
- As an alternative to formal and highly detailed reprourement drawings and specifications, require less formal drawings and encourage more informal information transfer. For reprourement data, pay a fixed amount for the drawings plus a fixed amount for each equipment successfully delivered by the second source.

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REFERENCES AND NOTES FOR PART I

1. In this table, RDT&E, Procurement, and Support each includes those portions of O&M and Military Personnel costs that are allocable to that category. Support costs further include depreciation of maintenance equipment and facilities, spares costs, and warranty costs. The figures quoted entail a number of judgments in the allocations, and these limit their accuracy somewhat without affecting the validity of the conclusions based on them. For a more detailed breakdown, see Table II-2 in Section II-G of this report. For a detailed discussion, see Appendix B.
2. The data in Fig. II-5, Section II-H of this report, show a statistical relation between unit production cost of avionics equipment and mean flight hours between failures (MFHBF); namely,

$$\text{Unit Production Cost} \times \text{MFHBF} = \$1.3 \times 10^6 \times \text{hours}.$$

Since the costs of support are roughly proportional to $(1/\text{MFHBF})$, this implies that unit support cost is proportional to unit production cost. An analogous conclusion is reached in IDA Study S-392, Avionics Performance and Costs, Vol. I7, December 1971, relative to the more narrowly defined maintenance cost (direct labor, materials, and replacement spares) being proportional to unit equipment cost.

3. Sections III-A-2, III-A-3, and IV-G of this report.
4. Section III-A-5 of this report.
5. Annex to Section III-A of this report.
6. Section III-B of this report.
7. Section III-C of this report.
8. Section IV-D of this report.
9. Section IV-B of this report.
10. Section III-C of this report, as well as address by Dr. John S. Foster, Jr., before Armed Forces Management Association/National Security Industrial Association Symposium, 16 August 1972.

11. Table I-II-30, Section III-C-4 of this report.
12. Fig. II-5 and associated text.
13. Section III-D of this report.
14. Section IV-A of this report.
15. Section III-E of this report, particularly Tables III-33 and III-34. Also, Office of the Assistant for Cost Analysis, U.S. Army Safeguard Systems Office, Should Cost/Will Cost/Must Cost--A Theory of the Cause of Cost Growth, June 1972.
16. Section III-E of this report.
17. See also Electronics-X Working Papers 21 and 23, available at the IDA Library.
18. Section III-F-1 of this report, particularly data such as Table III-35.
19. Section III-F-1 of this report.
20. Based in part on numerous discussions with industry personnel who cannot be quoted directly.
21. Section III-F-2 of this report.
22. Table II-2 and Appendix B to this report.
23. Section III-G of this report.
24. Section III-G-2 of this report.
25. Section IV-A of this report.
26. Section IV-E of this report.
27. Section IV-B of this report.
28. Section II-J of this report.
29. Section IV-C of this report.
30. Section IV-F of this report.

II. BACKGROUND AND UNDERLYING ISSUES

It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something.

--Franklin Delano Roosevelt

A. TASK

The Electronics-X Study, as stated in the Defense Advanced Research Project Agency's task assignment¹ to IDA, was "to identify and evaluate current and alternative DOD and industry policies, procedures and practices in development, production and operational support (of military electronics equipment) which most significantly influence acquisition and life cycle costs and field reliability and to recommend changes and improvements to reduce and control such costs and improve reliability." The study has taken into account the published results of concurrent related efforts undertaken under DDR&E sponsorship by other organizations.

The program sponsor requested that the study recommendations give emphasis, where possible, to specific mechanisms by which the Department of Defense might implement recommended changes in policies, practices, and procedures, and that the relative impact of implementing the recommendations be assessed.

B. PURPOSE

The motivation for the Electronics-X task assignment is given in the following statement:¹ "Sharply rising costs of electronics systems and unsatisfactory field reliability mandate an initiative by DDR&E to lower the costs of military electronics equipment and improve

its field reliability/maintainability, while still attaining acceptable performance and schedules." In later sections (II-H and II-I) we shall discuss the validity of the foregoing assertion and of the underlying assumption that, in fact, electronics costs can be reduced and reliability improved.

C. SPONSOR

The Electronics-X effort was sponsored by the Assistant Director (Planning), Office of the Director of Defense Research and Engineering.

D. RELATED EFFORTS

Several important study efforts have been completed in the recent past, the objectives of which were exposing and suggesting solutions to the problems of military equipment acquisition, reliability and maintenance. The reports of the efforts on which the Electronics-X Study has drawn most heavily are:

- Report of the Defense Science Board Task Force on Weapon-System Simplification (1970 Summer Study), sometimes known as "the Phillips Report," which considers the problem of over-specification of U.S. weapon-system capability. The report recommends early establishment of weapon-system cost goals, iterative examination of alternative solutions and their costs, and continuing tradeoffs of performance, cost, and schedule throughout the development cycle; recognition of excessive projection of enemy threats; identification of the few inviolable weapon-system performance requirements; use of proven components and subsystems; competitive prototyping; authority to reprogram cost savings; and purging of unnecessarily detailed specifications and requirements and of the offices that generate them.

Report of the Defense Science Board Task Force on Avionics (U), February 1973 (S), sometimes known as "the Fubini Study," which pointed out that tactical-mission avionics acquisition

costs are rising rapidly while defense equipment budgets are declining, leading to an almost inevitable reduction in force levels; and that these acquisition costs are but the tip of an iceberg: invisible, below the surface, lie the massive installation and maintenance costs, which constitute 50 percent or more of avionics life-cycle costs.

- Report of the Defense Science Board Task Force on Reducing Costs of Defense System Acquisitions, March 15, 1973, sometimes known as "the Bucy Report," which compared military and industrial practices in the development and procurement of defense systems.
- Report of the Commission on Government Procurement, December 1972, which dealt with the promotion of economy, efficiency, and effectiveness in the procurement of goods and services by the Executive Branch of Government.
- Cost Growth in Major Weapons Systems, March 26, 1973, a report by the Comptroller General of the United States to the Committee on Armed Services, House of Representatives, concerned with the problem of unforeseen cost escalation in military procurement and recommending adoption of certain managerial practices.

As further background, Report From Wasteland, written by Senator William Proxmire, a severe critic of current Defense Department practices, has proved educational. It challenges not only the efficiency but also the integrity of the military procurement process.

E. FOCUS

There are three specific differences between the Electronics-X Study and those major efforts that have preceded it. The first and most obvious of these is in the focus of Electronics-X on military electronics as a whole, as opposed to the broader perspective of weapons systems or the narrower view of avionics.

The second difference between the Electronics-X Study and most of those that preceded it is that it focuses on reduction of total cost of ownership, rather than just reduction of acquisition costs. The study has been impelled in this direction by the Fubini Study, which pointed up the large, largely uncontrollable, post-acquisition costs of ownership of electronic equipment.

The third aspect of this study that makes it different is its focus on the policies, practices, and procedures by which the Department of Defense may reduce the cost and increase the reliability of the electronic equipment it buys and uses.

F. WHAT'S DIFFERENT ABOUT ELECTRONICS?

It is useful to list those characteristics that set electronics apart from other items procured by the military, in order that one may understand why electronics is or should be treated differently.

First, although electronics may stand alone in communications, surveillance, electronic warfare, or tactical data processing systems, it is most commonly found imbedded in--and more or less integral with--weapons systems, the capabilities of which are dependent upon electronic elements. Electronic equipment represents a large and growing fraction of military weapons systems. Roughly 80 percent of the dollar value of military electronics is in aircraft, missile, and ship installations (Table II-1).

Second, the explosive technological growth in electronics has, in recent times, been far more rapid than the growth of any other branch of military technology. Efforts at taking advantage of this evolution in the context of system acquisition practices geared to more stable technologies have led to acquisition and maintenance cost excesses. Approaches specific to electronics appear to be warranted.

Third, the rate of development of electronics is, in several areas such as microelectronics, information processing, and display technology, driven by commercial rather than military markets--an abrupt turnabout from previous years. On the other hand, the rapid

technological advances in light intensifiers, lasers, infrared detectors, inertial sensors, phased arrays, and cryogenic systems are still driven by military rather than commercial needs.

TABLE II-1. ELECTRONICS COSTS FOR WEAPONS SYSTEMS AS PERCENTAGES OF WEAPON-SYSTEM PROCUREMENT COSTS AND OF ELECTRONICS PROCUREMENT BUDGET

<u>Electronics for:</u>	<u>Percentage of Weapon-System Procurement Cost^a</u>	<u>Percentage of Electronics Procurement Budget</u>
Aircraft	30%	31%
Missiles	75	33
Ships	20	16
Ordnance and Vehicles	6	4
Communication & Electronic Systems	100	16

^aSource: Ref. 2.

G. MAGNITUDES OF MILITARY ELECTRONICS EXPENDITURES AND INVENTORY

The budget of the Department of Defense for FY 1974 is \$81.1 billion. Of this total, \$8.1 billion is allotted to RDT&E, \$16.5 billion to procurement, \$21.7 billion to operations and maintenance, and \$22.5 billion to military pay and allowances. The total electronics content of the DOD budget is estimated² at \$15.3 billion, allocated among RDT&E, procurement, and maintenance as in Table II-2.

The clear preponderance in the Government's share of maintenance expenditures, which amounts almost to a Government monopoly, is significant. Its problems and its virtues will be discussed subsequently. As discussed in Appendix B (in Vol. 2), there is an evident dominance of indirect costs over direct costs that contributes to severe estimating uncertainties, a problem that will be discussed in a later chapter.

TABLE II-2. ALLOCATION OF TOTAL ESTIMATED ELECTRONICS
CONTENT OF FY 1974 DOD BUDGET AMONG RDT&E,
PROCUREMENT, AND MAINTENANCE

	<u>Billions</u>
<u>RDT&E</u>	
Electronics Content, RDT&E Contracts	\$2.9
Government In-House Electronics RDT&E	1.2
	<hr/>
Total Electronics Content, RDT&E	\$ 4.1
<u>Procurement</u>	
Electronics Content, Aircraft Procurement	\$1.6
Electronics Content, Missile & Space Procurement	1.7
Electronics Content, Ship Procurement	0.8
Electronics Content, Ordnance & Vehicle	0.2
Electronics Content, Electronics & Communications Procurement	0.8
Government In-House Electronics Procurement Support	0.7
	<hr/>
Total Electronics Content, Procurement	5.8
<u>Maintenance</u>	
Contract Electronics Maintenance & Support	\$0.4
Government In-House Electronics Maintenance	5.0
	<hr/>
Total Electronics Content, Maintenance ^a	5.4
	<hr/>
TOTAL ESTIMATED FY 1974 MILITARY ELECTRONICS EXPENDITURES	\$15.3

^aSource: Ref. 2.

The value of the in-use electronics inventory is a question of interest, since it is this inventory that determines the requirements for electronics maintenance. From Appendix B, the inventory is estimated as shown in Table II-3.

TABLE II-3. ELECTRONICS CONTENT OF DOD EQUIPMENT INVENTORY
(dollars in billions)

	<u>All Equipment</u>	<u>Electronics Content</u>	<u>Electronics Percentage</u>
Military Equipment in Use	\$110.1	\$31.1	28%
Military Equipment in Supply System	44.1	9.7	22
Total DOD Inventory	\$154.2	\$40.8	26%

The sheer magnitude of the \$15.3 billion figure associated with military electronics expenditures for a single year is impressive and provides such leverage that even small improvements in acquisition and maintenance practices can potentially save large amounts of money. The huge cost of electronics-related support has not been amenable to accurate estimate, largely because of the inadequacy of the DOD cost accounting system in establishing the cost of direct labor and, more particularly, overhead to repair electronic equipment and systems that fail in field operation. Our estimate indicates the total FY 1974 electronics maintenance costs to be about \$5.4 billion, or annually about 17 percent of the estimated in-use electronics inventory value of \$31.1 billion.

The astonishing aspect of our estimates is that in FY 1974 the electronics support cost almost equals the electronics procurement cost. Because force readiness and combat capability depend on effective support of existing weapons, in periods of declining military budgets and rising manpower costs, such as the current epoch, one can expect support expenditures to decline more slowly than procurement expenditures, and the ratio of support expenditures to procurement expenditures to increase.

H. VALIDITY OF THE STATEMENT OF THE PROBLEM

Despite the increasing utilization of electronics in military weapons systems and the increasing dependence of these weapons systems upon electronics for attainment of the specified weapon-system performance, the percentage of the defense budget going to electronics, excluding electronics-associated military personnel costs, is declining. Figure II-1 shows the estimate of the Electronic Industries Association (EIA)³ of the electronics content of the defense budget for Fiscal Years 1962-1974.*

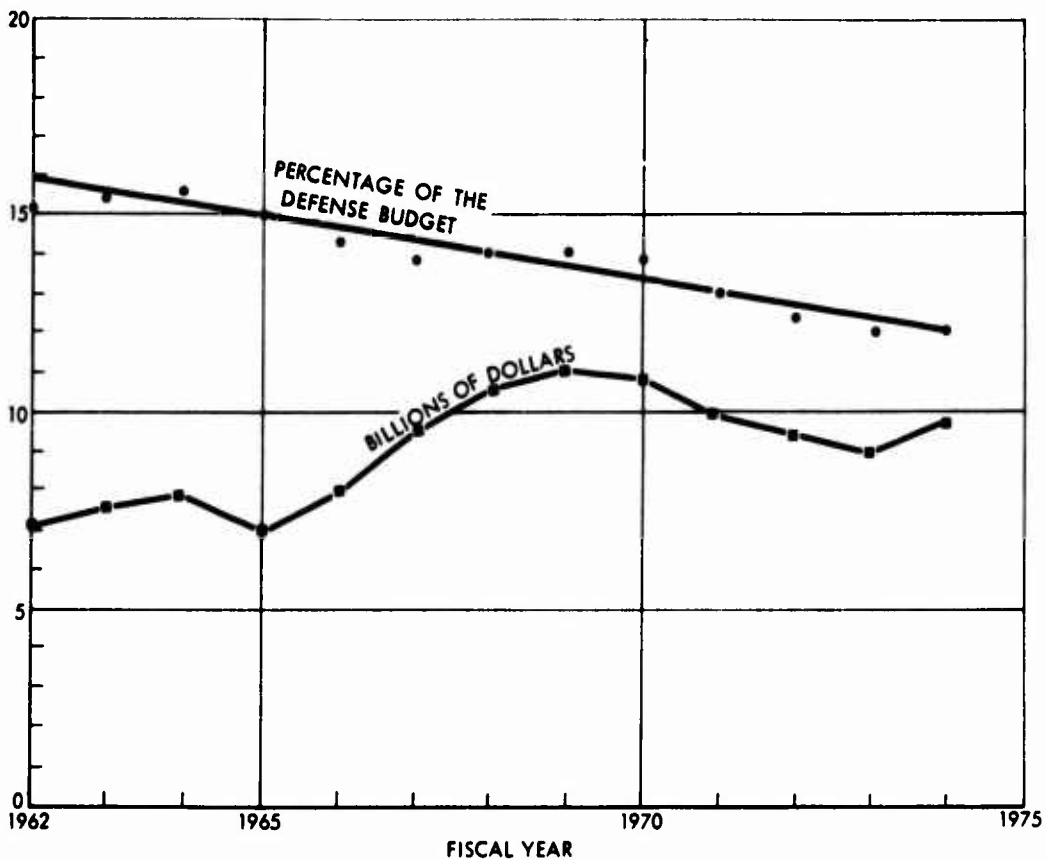


FIGURE II-1. Electronics Content of the Defense Budget (EIA Estimates)

* The EIA estimates are smaller than ours, but are used here to preserve consistency in the method of estimating over the 13-year period depicted.

During the period 1960-1970, Pelehach⁴ estimates that electronic reliability on a per-part basis has grown by an average factor of 4, as illustrated in Fig. II-2.

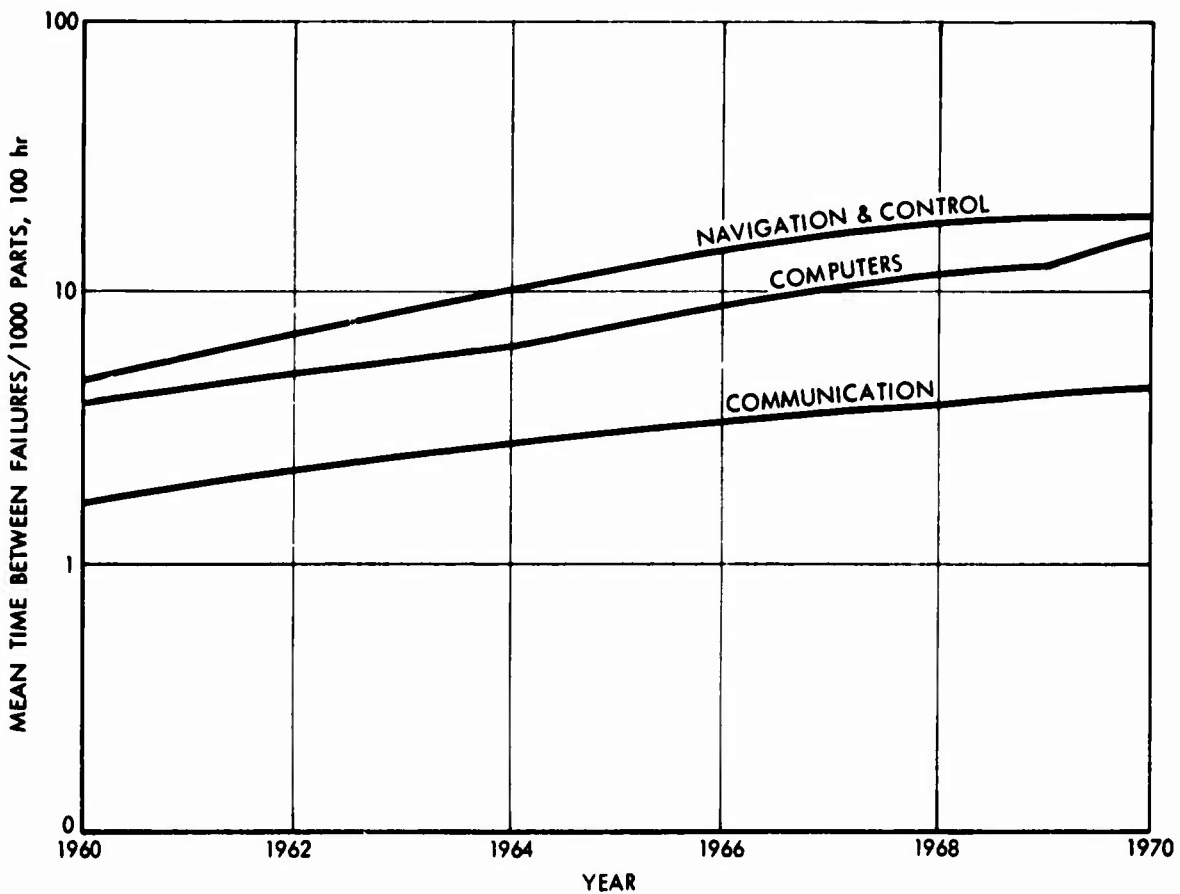


FIGURE II-2. Avionics Reliability Trends

It is paradoxical, then, that electronics is seen to be increasing in cost and to be of unsatisfactory reliability, and it is important to the discussion that follows that the reasons underlying this perception be understood.

One aspect of concern lies in the rising cost of military manpower, which now constitutes 32 percent of the military budget, as opposed to 26 percent in 1964. The economic cost of an Army electronics technician at the E-5 level, for example, has risen 39 percent

since 1966.⁵ During the same period, the implicit GNP deflator has risen by only 28 percent. Secondly, the military electronics inventory is estimated to have grown by 10 percent in the last four years. Such growth, combined with the increase in cost of the personnel needed to maintain the inventory, would account for a perceived escalation in the aggregate cost and the fraction of the budget devoted to electronic maintenance. Finally, individual electronic systems and subsystems are getting bigger (Fig. II-3), costlier, and more complicated.

Figure II-4 illustrates the cost growth trend for new types of combat aircraft.⁶ An average growth rate over more than five decades of about 12 percent per year, or a factor of 3.1 per decade, is indicated. Though the electronics content varies from aircraft to aircraft, the average electronics fraction of total aircraft cost has increased from about 10-20 percent in the 1950s to 20-30 percent in the late 1960s and early 1970s.⁷ Thus, the new-generation avionics cost increases at a rate of perhaps 18 percent per year, more rapidly than the new-generation aircraft cost. Though combat aircraft have been used as an example, similar trends exist in other weapon systems.

The relationship between unit production cost and field reliability is illustrated for Air Force avionics equipment by Fig. II-5, the data points of which have been drawn from a number of sources,⁸ and include tube, transistor, integrated-circuit, and hybrid equipments of various vintages. Both cost and reliability are functions of equipment complexity. As complexity increases, cost increases and reliability, as measured by mean flight hours between failures (MFHBF), decreases. Thus, Fig. II-5 shows a median relationship* in which

$$\text{MFHBF} = 1.3 \times 10^6 / \text{cost} .$$

* A similar relationship based on limited data is found for Army Area Communications Systems (AACOMS): Field MTBF = $10^7 / \text{cost}$.

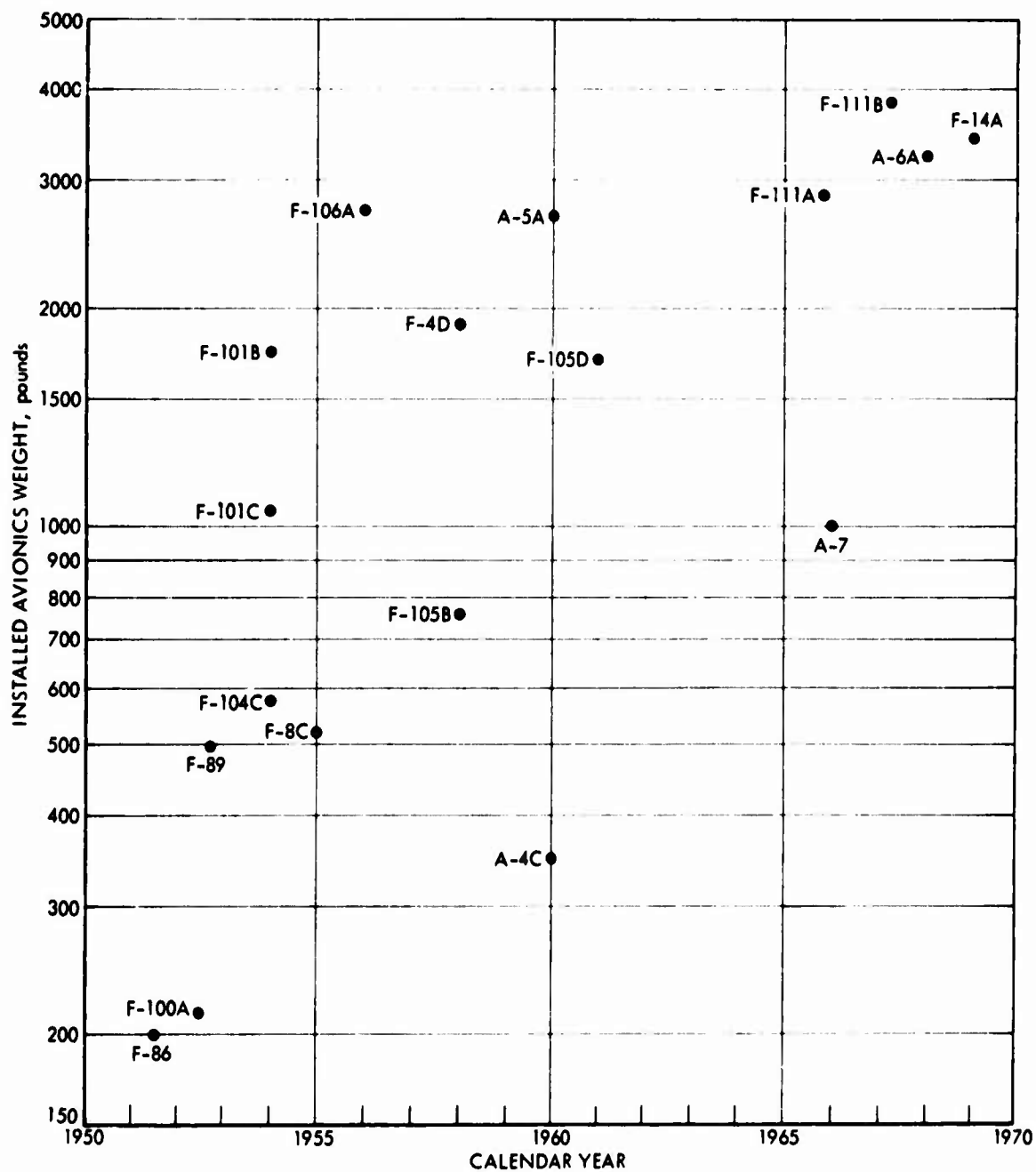


FIGURE II-3. Avionics System Weight Trend in Attack and Interceptor Aircraft (from Pelehach)

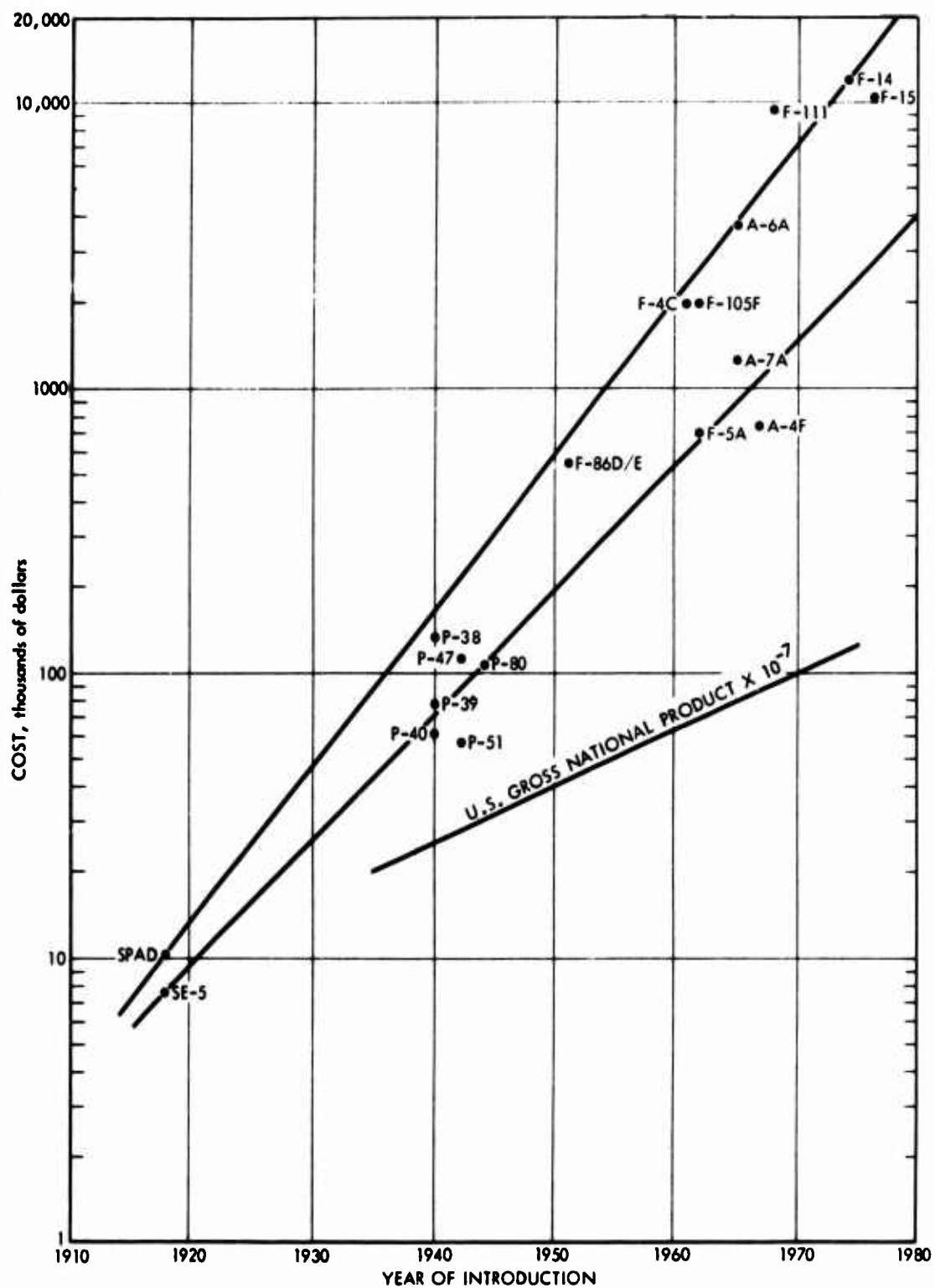


FIGURE II-4. Cost of Combat Aircraft

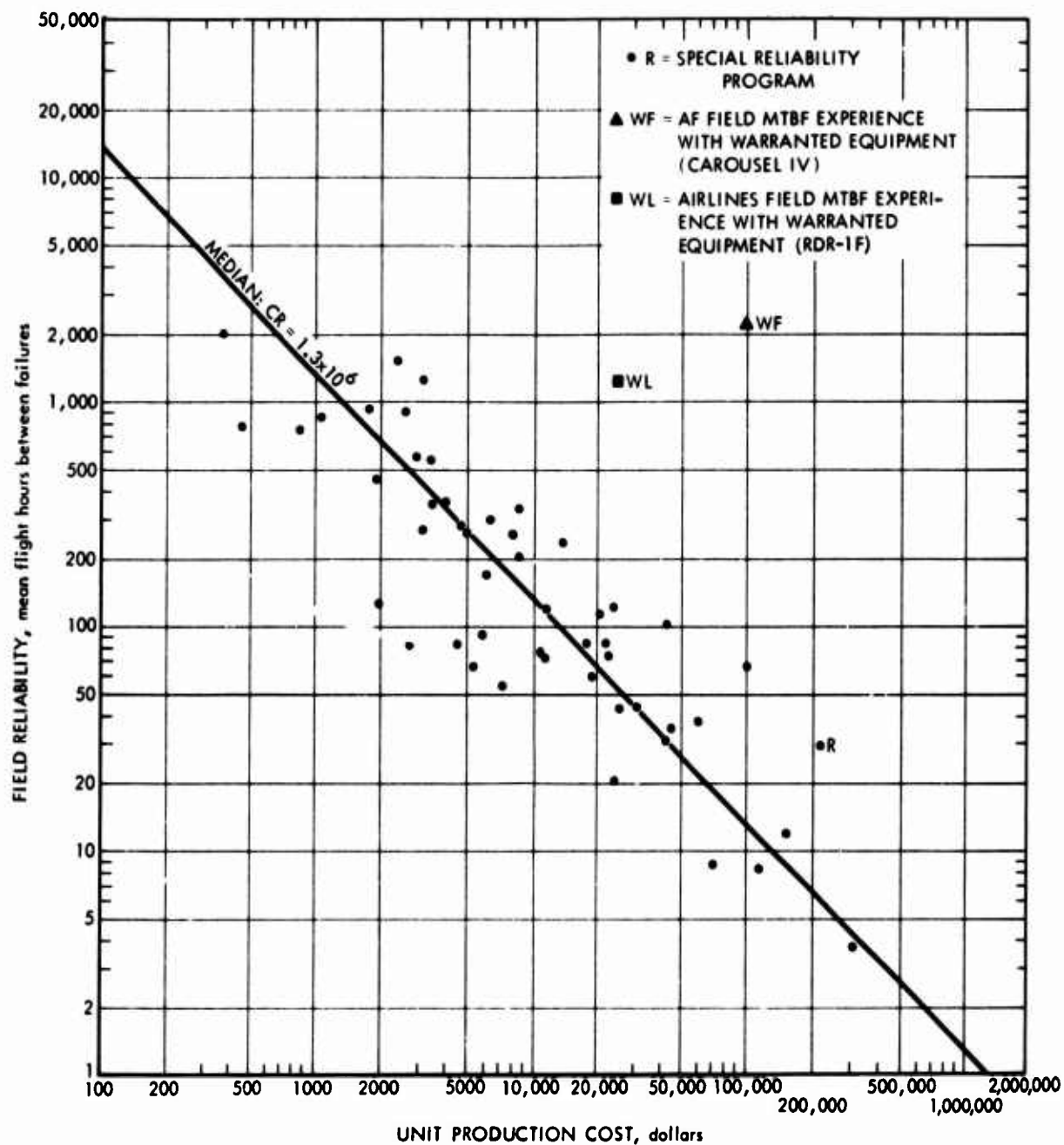


FIGURE II-5. Avionics Field Reliability versus Unit Production Cost
(See Appendix E for source data)

From this relationship, field reliability of avionics can be crudely predicted (within a factor of 3) when cost is known. If, for example, an equipment costs \$100,000, it can be expected to have an MFHBF of 13 hours; if it costs \$1,000, the expected MFHBF is 1,300 hours.

The inverse MFHBF-versus-cost relationship of Fig. II-5 explains the frequent occurrence of the question, "Why, when my electronic equipment is so expensive, is it so unreliable?"⁹ It also shows why annual repair costs for avionics can be crudely estimated as a constant fraction of production cost: failure rate is proportional to production cost, and annual repair costs are proportional to failure rate.

It now becomes much clearer why electronics cost and reliability excite concern. The costs of new-generation weapons systems electronics have been rising at rates of between 15 and 20 percent per year, which means that the number of weapons systems that can be purchased from a fixed budget is rapidly declining. At the same time, the annual 15 percent rate of growth in reliability of electronics as technology advances is, at best, barely keeping pace with the rate at which the complexity of new-generation weapons systems electronics is increasing, with the result that electronic subsystem reliability is at a standstill.

I. IS THE PROBLEM SOLVABLE?

Simplify, simplify.

--Henry David Thoreau

The question remains: Can the problems of excessive cost and inadequate reliability of military electronic equipment be solved?

Figure II-5 yields indications of potential solutions. The first of these derives from the empirically observed trend showing that reliability goes down when unit production cost goes up. An equipment of half the unit production cost (and, consequently, half the complexity) of another can be expected to have twice its reliability.

This suggests that if requirements can be purged of complicating but unnecessary performance stipulations, and if equipment specifications can be stripped of difficult but nonessential design demands, simultaneous reduction in cost and improvement in reliability might be attained.

The second observation to be made from Fig. II-5 is that there is substantial spread in the results: certain equipments are three or more times more reliable in the field for a given cost than the median. Among these are three data points in Fig. II-5 that deserve special attention.

All three represent cost versus reliability for avionic equipments that underwent special programs for the development of reliability. (The results of the three are not directly comparable to each other because of differences in operating environment and methods of reliability measurement.) The point R represents the General Electric AN/APQ-113 radar^{10,11} for the F-111 aircraft. The point WL represents the Bendix RDR-1F weather radar used by commercial airlines and maintained by the supplier under contractor maintenance warranty. The point WF represents the Delco Carousel IV inertial navigator used by commercial airlines and the U.S. Air Force and also required to be maintained under warranty. For these it can be deduced that there existed design, workmanship, and parts-selection criteria and development approaches that yielded very superior results, and it may be inferred that these approaches can be found for other systems and applied, if there is adequate incentive to do so. The search for such approaches forms a major theme of this report.^{12,13}

The relationship of MFHBF to unit production cost shown in Fig. II-5 suggests a realizability criterion for avionics reliability, in the absence of a more direct criterion based on complexity and technology. A realizability criterion is essential to answering such questions as, "Is my equipment as reliable as it could be?" and "Which are the problem equipments?" From Fig. II-5, it appears that the superior equipments attain a field MFHBF of about $6 \times 10^6/\text{cost}$, as opposed to the median of $1.3 \times 10^6/\text{cost}$.

With the knowledge of what is attainable with difficulty and what is commonly achieved, one can take a further step to establish an unacceptability criterion for avionics reliability. Figure II-5 represents observed results, but many of the equipments represented are old, using vacuum-tube technology, and represent designs in which reliability was given little or no attention. New equipments should easily exceed the old median results. The reliability attainable with special effort in development exceeds the old median by a factor of 4.6. Thus, a suggested lower limit of acceptability is the old median:

$$\text{Field MFHBF} = 1.3 \times 10^6 / \text{cost} .$$

Applying this criterion to the existing avionics inventory would, of course, indicate that half the models in the inventory have less than readily achievable reliability and should be candidates for improvement or replacement.

J. MILITARY UTILIZATION OF ADVANCING ELECTRONICS TECHNOLOGY

For the commercial market, the advance of technology has meant, in part, successive reductions of cost and weight and increased reliability for given functional components and systems. As a typical example, an electronic calculator of 1962 vintage had about 3000 transistors, weighed 40 lb, and was priced at \$2200, while the equivalent 1973 calculator performs identical functions, uses two MOS devices, weighs 2 lb, and costs \$170. Such evolution in many areas has opened vast new markets and led to rapid expansion of commercial electronic manufactures. In industrial applications, modern electronic technology has permitted the development of new devices and systems to perform functions that, previously, could only be done with difficulty or not at all. The examples of computing cash registers, computerized system and process controls, electronic ignition and skid control in automotive design, and automated warehouses suggest the broad range of products and markets thus made available.

In contrast, until the recent advent of the "design-to-cost" philosophy, little effort was devoted by the Services to the application of new technology to military electronics with the specific objective of reducing costs (or increasing reliability) while preserving performance. Rather, technological advances have been used to increase performance, obtain greater precision, and add functions to the extent feasible--often at substantial cost in dollars and reliability because of the sheer magnitude of the increase in number of circuits and components or the exquisite manufacturing precision required. The following unit hardware production cost increments crudely indicate the cost of adding performance to military electronic systems:

- To extend the range of an air-to-air radar, about \$6,000/mile.
- To go from a basic, noncoherent airborne radar that can show large terrain features to an attack radar system with MTI, accurate mapping, ranging, and resolution of a few tens of feet, about \$250,000.
- To increase the target acquisition cone in the guidance system of a short-range air-to-air missile, about \$3000/10 deg.
- To gain the range increment from accurate fire of a missile rather than a gun on a tank, the cost of the fire control system increases about \$100,000/km of range.
- To increase the accuracy of an airborne inertial navigation system by an order of magnitude, about \$500,000.

The consequences of the military focus on performance and functional capability have been significant:

1. While the cost per active electronic element has decreased by two orders of magnitude or more in the progression from vacuum tubes to MOS,¹⁴ the growth of functions has led to a net increase in the number and cost of system parts. Thus the reliability trend for electronic systems and subsystems has been stationary or downward.

2. To counteract the downward trend in system reliability occasioned by increased complexity, there has been increased emphasis on parts inspection, test, selection, and traceability at a substantial cost increment to the military over the cost of equivalent commercial parts.
3. The DOD share of the market is only 20 percent and is declining in microelectronics and certain other areas of electronics. Where military needs are special--that is, where commercial parts are not used--DOD must pay the high cost of special designs, captive or dedicated production lines, small production runs, and special quality-control arrangements.

There are a number of alternatives available to the military, and they will be discussed in more detail in subsequent chapters of this report. The fact that commercial technology is turning over every 3 to 5 years in microelectronics and certain other areas, while military development takes 7 to 10 years from inception to inventory, suggests that some portions of military electronic designs are obsolescent by the time they are deployed.

This, in turn, suggests the alternative that the military permit utilization of more commercial parts and free itself from dependence on rigorous military specifications that demand premium and perhaps outmoded components. To do so, the military needs to depend more on specification of equipment form, fit, function, and interface and less on specification of detailed designs. By so doing, the military may also admit more modified commercial designs to military competitive procurement. It may also be desirable to provide controlled environments for equipments in order to increase the utility of commercial components and equipments.

Freedom to use the most advanced of available technology, accompanied by the search for design simplicity implied in the design-to-cost approach¹⁵ and the evolution of reliability through use of the iterative test-and-fix process,¹³ represent a method of utilizing

technology in military electronics that represents a sharp departure from the prior approach of seeking performance regardless of cost and reliability outcomes. The use of specifications for form, fit, and function and of interface standards to ensure interchangeability of competing designs¹⁶ can provide a greater choice of equipment for DOD and increased incentives for suppliers to progress toward the objectives of simplification, reduced cost, and increased reliability.

K. THE MILITARY ELECTRONICS LIFE-CYCLE PROCESS: A MAJOR FLAW AND A POSSIBLE REMEDY

We must learn to explore all the options and possibilities that confront us in a complex and changing world.

--James William Fulbright

Competition is a pervasive theme that has emerged in this and several past studies of systems acquisition management. The value of competition in helping to keep costs down and in maintaining options appears intuitively self-evident. Many examples of cost reduction through competition came to light during this study. However, such data are largely scattered and, in many cases, anecdotal. The small amount of systematically derived quantitative evidence that exists to support the efficacy of competition is presented and discussed later in this report. For the rest, the qualitative and quantitative evidence has been taken as positively suggestive enough to warrant building much of our analysis around the theme. But the reader should bear in mind that much of this is based on the assumption, yet to be validated by experience, that competition throughout the electronic-system life-cycle process will, on the whole, yield great benefits in reduced cost, greater equipment reliability, and availability of options at critical selection points in that process.

As shown previously, the cost and reliability problems that are increasingly evident in military electronics, arising in large measure from the disparity in magnitude and direction of development and application between civilian and military technology, imply that the

DOD must change its approach to acquiring and maintaining electronic equipment. The sum of these changes would, if integrated around the theme of increasing competition at all stages of the life cycle, be reflected in the life cycle of military electronic systems, as illustrated in the following discussion.

The life-cycle process of electronic equipment and systems can be roughly partitioned into four phases, each of which involves one or more steps:

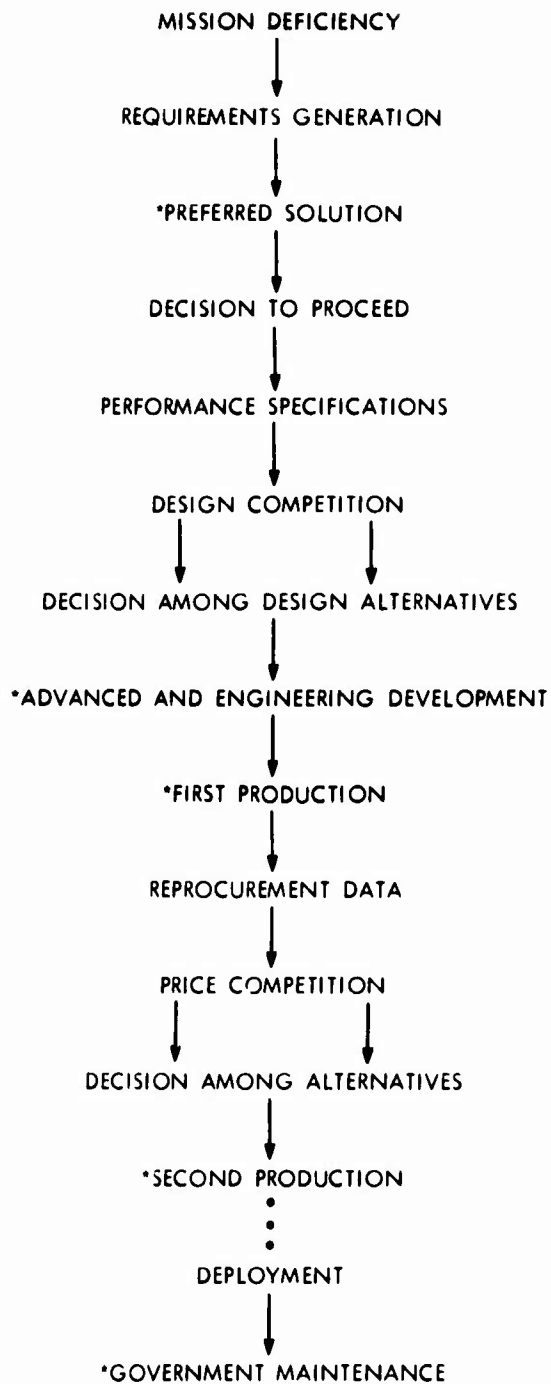
1. Requirements and acquisition decisionmaking
2. Development
3. Production
4. Operation and maintenance.

Ideally, at each step, there should exist

- Established goals
- Goal-oriented incentives
- Competing alternative courses from which the decisionmaker may choose
- Visibility of the consequences of each course of action.

It has become apparent in this study that at most of the steps comprised in the life-cycle process for military electronics, one or another of these elements is missing. Of the missing elements, possibly the most consequential is the lack of competing alternatives, for when the decisionmaker has a choice to make, he will be driven to research the goals, incentives, and consequences in order to rationalize his decision.

Figure II-6 illustrates what is meant by a paucity of alternatives in a hypothetical worst case. In this case, after statement of a mission deficiency and generation of a set of requirements, a preferred conceptual solution is decided upon and advocated, while alternatives are discarded. Performance specifications based on the preferred concept are prepared, and a design competition is undertaken from which a single design is selected. Design offerings that do not reflect the preferred concept are rejected as "nonresponsive." The



*WHERE ENHANCED COMPETITION AMONG POTENTIAL ALTERNATIVES COULD BE UNDERTAKEN.

FIGURE II-6. Inadequate Alternatives in the Electronics Life-Cycle Process

selected design is developed to completion, perhaps at a greater cost and in a longer time than anticipated, for there are no choices. The first production is necessarily of the chosen design, even though it may not be as economical in meeting the mission deficiency as other possible designs. Because competing designs have been eliminated, the second production is identical in design to the first one, although there may be a price competition. Finally, the deployed equipment is maintained by military maintenance organizations; no alternative is considered, although some may be possible.

The asterisks in Fig. II-6 designate steps in the electronics life-cycle process where, we believe, alternatives could usefully be developed, and where competition among concepts, designs, prices, and suppliers could be enhanced. Subsequent sections of this report will deal in detail with the means and mechanisms by which this can be done. and with the potential value of doing it. Substantial changes in requirements, acquisition, and maintenance practices would be needed to provide these means and mechanisms. If such changes were made, the hypothetical process shown in Fig. II-6 could take on the form of Fig. II-7, in which double arrows indicate that more than a single choice is available at a step.

With enhancement of alternatives, as shown in Fig. II-7, a mission deficiency would trigger the generation of a requirement. A dollar target, a schedule, and a quantity consistent with military priorities and available funds would be associated with the requirements statement. Alternative solutions, representing both product-improvement and new-generation approaches, would be compared as to cost and effectiveness; at least one of each kind would be pursued whenever feasible, if there were a decision to proceed. Approaches having high risk would be set aside, and the high-risk problems would be specifically attacked before proceeding. Performance specifications, complete with interface standards, would be prepared in a way that would assure interchangeability of designs developed to the specifications, and would maintain the possibility of design and price

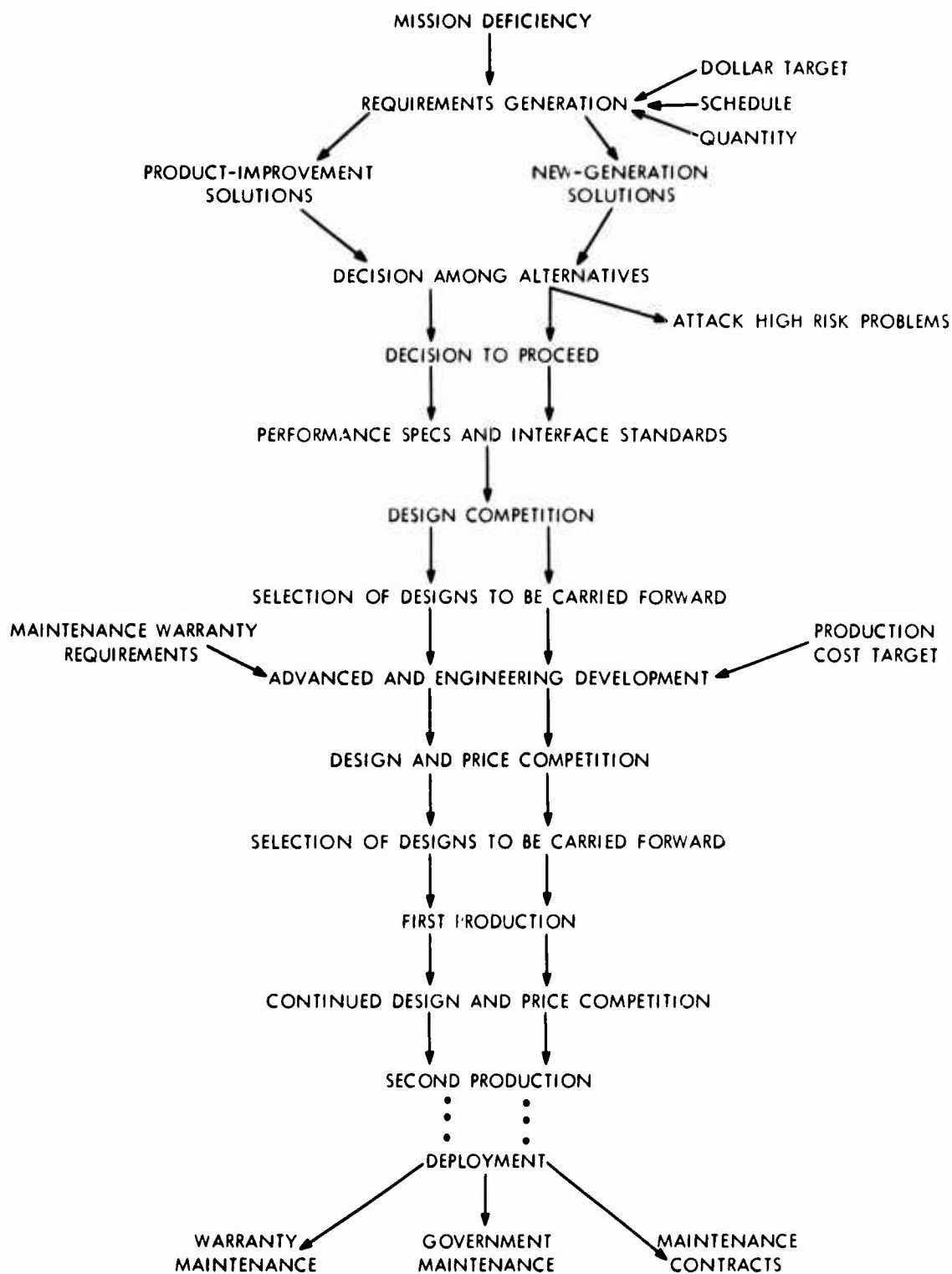


FIGURE II-7. Enhancing the Alternatives

competition in subsequent production. After contractor design competition, at least two designs would be selected, if at all feasible, to be carried through development to the prototype stage. Production cost targets would be included as design parameters, and future maintenance warranty requirements would be stated, where appropriate and workable. A subsequent design and price competition would determine which designs were to be carried into first production. The proportion of the production award to each bidder might be based on the relative merits of the designs and prices, including price of warranty, if any; in some cases (e.g., few-of-a-kind systems), it would be preferable for the winner to take all. Suppliers would continue improving design and reliability to prepare for competition for the second production buy, if there were to be one, or to meet reliability guarantees and improve return on investment, even if there were no further production buy. Interchangeability of competing designs would remain assured by virtue of compliance with the interface specifications. Finally, upon equipment deployment, maintenance might be under supplier warranty, or, if there were no warranty, a selection might be made between military and contract maintenance on the basis of comparative costs and convenience.

The process just described implies incorporation of several important changes in the philosophy of system acquisition and maintenance. The changes can be generalized as follows:

1. Conceptual, design, price, and supplier alternatives must be made visible and must be sustained during the entire process, from requirements, through development and production, to maintenance.
2. Goals, particularly those of cost and reliability, would be stated.
3. Incentives for improving design would be provided by continuing competition between interchangeable designs. Incentives for life-cycle cost reduction would be provided wherever possible by the use of warranties and by provision

for alternatives to Government maintenance. Incentives for reconciling requirements, technology, and costs would be provided by the inclusion of cost as a design parameter.

While this formulation represents an approach that may not be achievable for all equipments or systems at all times, the results of this study suggest that it is an ideal worth striving to achieve, for large potential payoffs. It is likely to be more achievable for electronic systems and subsystems than for major weapons systems as a whole.

L. CONTENTS OF THE REMAINDER OF THIS REPORT

Part III, immediately following, discusses the uncertainties in the two metrics, cost and reliability, to which the Electronics-X Study was addressed. As the study proceeded, it became increasingly clear that the major findings would show certain key types of data to be virtually nonexistent; recommendations to remedy this situation are thus an important output of the study. The absence of valid quantitative information on past results in the areas of cost and reliability makes difficult the validation and use of models for life-cycle cost estimation, makes impossible even the loosest cost-benefit analysis of report recommendations, and prevents measurement of any changes introduced into practices, policies, and procedures. Recommendations for improved accounting and auditing procedures will be made.

Other findings and recommendations can be classified in two categories: (1) those based upon the sketchy and imperfect data available, and (2) those that could be assembled from qualitative, logical analysis circumventing the unavailability of data. First, in Part III, the electronics life-cycle process is discussed according to its phases: requirements, design and development, production, and maintenance. In each phase, some techniques are recommended by which electronics costs can be held down and reliability improved. The discussion concentrates on the key issues and the major ideas for resolving them that emerged from this study.

In Part IV, specific attention is given to the details of salient subjects referred to in Part III: warranties, standardization, software, configuration management, and project management.

The reader will recognize that there are no firm dividing lines between the ideas addressed in connection with each phase of the life cycle, or between the issues discussed in detail as special topics. The impact of actions in the requirements process is felt during development, production, and maintenance; design to cost has implications appearing at all phases of the life cycle; the issues addressed as special topics interact with each other and affect equipment throughout its life cycle. Thus, divisions have been made in the interest of clarity in presenting ideas in some logical order. Interactions and overlaps of ideas will be readily apparent as the presentation unfolds.

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2. Appendix B to this report.
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4. Michael Pelehach, Grumman Aerospace Corporation, The Influence of Avionics on Aircraft Design, presented at 35th Meeting of Flight Mechanics Panel of AGARD, Amsterdam, Netherlands, 2-5 September 1969.
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6. Alexander H. Flax, "Cost and Economic Factors in Aerospace System Development," in Management in Wissenschaft und Technik, Festschrift für Theodor Benecke zum 60. Geburtstag, Manfred Schroeder, ed., Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt E.V., Porz-Wahn, September 1971, pp. 176-209.
7. Section III-B of this report, particularly Table III-21.
8. For example, Arinc Research Corporation, Cost Study of Selected Communications, Navigation, and Identification Equipments, OE05-01-1190, June 1972.
9. A paradox that has vexed the U.S. Congress: see Congressional Record, Senate, S-1450, February 7, 1969.
10. Aerospace Electronic Systems, General Electric Company, Utica, N.Y., Reliability Planning and Management, J.D. Selby and S.G. Miller, September 26, 1970.
11. Reliability and Quality Assurance Staff, Aerospace Electronic Systems, General Electric Company, Utica, N.Y., Research Study of Radar Reliability ..., Technical Report ASD-TR-73-22, April 1973. (Prepared for Deputy for Engineering, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.)

12. Section IV-A of this report.
13. Section III-D of this report.
14. Electronics-X Subcontractor Report 6, p. D-19. (Available at the IDA Library.)
15. Section III-C of this report.
16. Section III-E of this report.

III. ACQUISITION AND SUPPORT

A. UNCERTAINTIES IN COST AND RELIABILITY

The Electronics-X Study was aimed at finding methods of reducing the cost and improving the reliability of military electronics. Subsequent sections of this report deal with various possibilities, for example: in the requirements process, associating a predicted cost with a military need; in design, designing to a specified unit production cost and to a mission-dictated yet attainable reliability; and in maintenance, using alternatives to Government maintenance.

The suggestion that methods of reducing cost and improving reliability can be found seems to carry with it the twin implications that currently realized cost and reliability are known and that cost and reliability are predictable, neither of which is strictly true.

It is possible, in principle, to measure the cost of development and production of an item by suitably aggregating contract costs. Prediction of program costs, however, has been inaccurate, to say the least.

Measurement of electronics maintenance costs, either by item or in the aggregate, has never been systematically undertaken, even though these costs, whether considered on an annual basis or over the life cycle of equipment, are of the same importance as procurement costs. Prediction of maintenance costs has been made the subject of numerous life-cycle models, but the absence of current data militates against either providing input parameters to a model or validating the predictions.

Measurement of reliability is undertaken in the factory or laboratory for much military electronics, but despite considerable attention

to the reporting of maintenance actions, systematic evaluation of reliability attained in the field is extremely difficult and usually is not accomplished. Prediction of reliability is frequently undertaken by equipment designers on the basis of aggregation of the anticipated failure rates of pieces and parts, but the predicted values thus obtained disagree by large factors with the values actually measured in the factory or reported from the field.

The following sections discuss inadequacies in measuring and predicting the cost and reliability of military electronics and recommend steps to remedy those inadequacies. A related subject, that of schedule prediction, is discussed briefly.

1. Cost-Estimating Uncertainties

One of the many critical areas that must be addressed if the cost of military electronics is to be reduced is the uncertainty in the present DOD ability to estimate the ultimate program costs associated with the acquisition and operation of electronics. These costs include the total program costs attributable to a new product or weapon system, including development, production, installation, and field operation and maintenance costs, whether incurred by Government or industry.

Uncertainties in cost estimation have become critical considerations under conditions of cost constraints on acquisitions and total program budgets. Adequate cost prediction capability is essential to making rational choices among alternative programs. Moreover, if the design-to-cost concept is to be successfully implemented by the DOD, realistic cost goals must be set, and uncertainties associated with those cost goals must be recognized, quantified, and reduced, if possible. Failure to improve electronics cost estimation will surely result in continued unexpected cost growth like that experienced to date.

a. Cost Growth in Acquisitions of Major Systems. The most consistent evidence of widespread inability to estimate equipment

acquisition costs has been the continuing cost growth of major weapons systems. Although evidence of cost-estimating uncertainties as exemplified by cost growth has always been available, the establishment in 1968 of Selected Acquisition Reports (SARs) for major systems provided recurring and more consistent cost-estimating information that documented the cost growth of those systems. In 1971, the SAR reporting system was amended to include information relevant to the causes for cost growth in addition to the actual revised estimates. This information provided by the SAR has made for increased visibility of the aggregate problems of cost growth and cost-estimating uncertainty.*

The SAR reporting system is built around three estimates of total program cost--a planning estimate, a development estimate, and a current estimate. The cost growth reflected in a comparison of these three estimates can vary considerably, depending on the relative timing of the estimates in the planning, development, and production phases of a program. As a program proceeds beyond DSARC II into full-scale development, the current estimate is periodically adjusted on the basis of experience and new projections of unit production cost and quantity. At DSARC III, initiation of full-scale production, the current estimate reflects actual expenditures incurred during development and the most recent estimate of total production cost. In theory, at least, the current estimate, as periodically compiled throughout development and production, will converge toward the total program cost at program completion. Comparison of planning, development, and current estimates is, therefore, likely to be valid as an indicator of cost growth only if the estimates have been made at comparable times in the planning, development, and production phases of a program.

Cost growth as shown in successive estimates during acquisitions of major weapons systems during the past 5 fiscal years, 1969-1973, is summarized in Table III-1, based on SAR data compiled by the

*The SAR system is not a unique reporting system. Previous reporting systems such as the Cost Information Report (CIR) presented much of the same data, and a new reporting system, the Contractor Cost Data Report (CCDR), will expand the cost data base and coverage.

General Accounting Office (GAO).¹ It is seen that the average cost growth from the planning estimate to the development estimate and from the development estimate to the current estimate has remained nearly constant. For the 5-year period, the average ratio of development estimate to planning estimate was 1.18, and the average ratio of current estimate to development estimate was 1.19. Although less cost growth is shown for some years than for others, the aggregate cost growth for the 5 years, represented by an average 1.40 ratio of current estimate to planning estimate, indicates that little significant progress is being achieved in reducing cost growth.

TABLE III-1. SUMMARY OF COST GROWTH REPORTED IN ACQUISITIONS OF MAJOR SYSTEMS^a

	Fiscal Year					5-Year Average
	1969	1970	1971	1972	1973 ^b	
Total Number of Systems Reported	57 ^c	61	77	45	45	57
Ratio of Development Estimate to Planning Estimate	1.19	1.15	1.16	1.15	1.25	1.18
Ratio of Current Estimate to Development Estimate	1.26	1.22	1.12	1.20	1.14	1.19
Ratio of Current Estimate to Planning Estimate	1.50	1.40	1.31	1.39	1.43	1.40

^aData source: Ref. 1; each system is assigned equal weight in this table.

^bData are from the December 31, 1972 reports, Ref. 1.

^cCost growth data available for only 38 of the 57 systems reported.

Further analysis of the GAO SAR data can provide additional insight into both the magnitude and the time relationship of cost growth as a program progresses through the development and production phases.

Among the 96 weapon-system programs reported by SARs during the 4-year period from FY 1969 through FY 1972, a survey of programs involving substantial amounts of electronics revealed annual current cost estimates for 16 programs during development (Table III-2) and 18 programs during production (Table III-3) that were suitable for analysis. Three programs (TOW, VAST-247, and Mark 48) appeared in both the development and production groups. In addition to the current cost estimates, Tables III-2 and III-3 show the reported planning and development cost estimates for the programs. The tables summarize program cost growth as a percentage of the earliest available estimate. Generally, the cost growth of an individual program has been measured from the planning estimate; otherwise, in the absence of a planning estimate, growth has been measured from the development estimate.

The summary data in Tables III-2 and III-3 are the basis for the trend lines in Figs. III-1 and III-2 (page 86), respectively, which indicate the course of the growth with time of the average program cost of the weapons systems during development and production.

For the programs in Table III-2 and in Table III-3 for which planning estimates were available, the weighted average* growths of total program cost from planning estimate to development estimate were 24 percent and 32 percent, respectively. For those programs beyond DSARC II and in full-scale development (Table III-2), the weighted average growth of total program cost rose from 22 percent in the first reported year of development to 43 percent in the fourth year. For those programs in the production phase (Table III-3), the weighted

*The weight assigned to each program was proportional to the initial estimate of total program cost. See Appendix F for details of the weighting method.

TABLE III-2. SUMMARY OF GROWTH OF TOTAL PROGRAM COST OF SELECTED PROGRAMS DURING DEVELOPMENT^{a,b}
(current dollars in millions)

Program	Planning Estimate (f, Date of Data)	Development Estimate (f, Date of Data)	Cost Growth at Development $x_i^{(d)}$	1st Reported Program FY of Development		2nd Reported Program FY of Development		3rd Reported Program FY of Development		4th Reported Program FY of Development	
	p_i	$c_i^{(d)}$	$x_i^{(d)}$	Current Estimate (f, Date of Data)	Cost Growth $x_i^{(1)}$	Current Estimate $c_i^{(2)}$	Cost Growth $x_i^{(2)}$	Current Estimate $c_i^{(3)}$	Cost Growth $x_i^{(3)}$	Current Estimate $c_i^{(4)}$	Cost Growth $x_i^{(4)}$
B-1	\$8,800	(6/69)	\$10,108	(6/70)	(6/70)	\$11,952	\$3,152	\$11,364	\$2,564	\$11,277	\$2,477
F-15	6,039	(6/69)	7,355	(6/70)	(6/69)	8,120	2,081	8,144	2,105	8,147	2,108
AMACS	2,653	(6/69)	2,662	(6/70)	(6/70)	2,727	74	2,727	74	2,683	30
CHEYENNE	-- ^d		126	(6/69)	(6/70)	202	76	293	167	332	206
TOW	410	(6/69)	727	(6/70)	(6/69)	945	535	709	299	746	336
LANCER	544	(6/69)	653	(6/70)	(6/69)	852	308	855	311	790	246
SPARROW F	140	(6/70)	708	(6/70)	(6/69)	1,084	944	1,297	1,157	1,306	1,166
PHOENIX	371	(6/69)	677	(6/69)	(6/69)	1,022	1,141	1,278	907	1,126	755
F-14	-- ^d		6,166	(6/69)	(6/69)	6,373	207	8,573	-851	5,337	-829
S-3A	1,764	(6/69)	2,891	(6/69)	(6/69)	2,891	1,127	2,954	1,190	3,276	1,512
CONDOR	117	(6/69)	126	(6/69)	(6/69)	167	50	383	206	596	479
MAVERICK	258	(6/69)	392	(6/69)	(6/69)	375	117	384	126	481	223
TACFIRE	124	(6/70)	160	(6/70)	(6/70)	188	64	218	94	237	113
VAST-247	241	(6/70)	312	(6/70)	(6/71)	--	--	445	204	489	248
Mark 48	682	(6/69)	700	(6/69)	(6/69)	--	--	3,891	3,209	3,785	3,103
REGIS	388	(6/70)	428	(6/70)	(6/70)	441	53	484	96	--	--
\bar{x}			\$ 383.43			\$ 465.77	\$ 886.14	\$ 758.56	\$ 811.53		
n			14			13	14	16	15		
\bar{p}			\$1,603.36			\$2,114.62	\$1,392.86	\$1,801.44	\$1,895.67		
Weighted Average Program Cost-Growth			24%			22%	44%	42%	43%		
Trend Line ($\langle u \rangle = x/p$)											
Weighted Standard Deviation (σ)			+36%			+28%	+59%	+95%	+96%		

^aSource of data: Ref. 1.

^bFor notes on method of computation and weighting, see Appendix F.

^cCost growth over earliest available estimate (planning estimate, if reported; otherwise, development estimate).

^dLack of planning estimate results from late SAR reporting requirement.

TABLE III-3. SUMMARY OF GROWTH OF TOTAL PROGRAM COST OF SELECTED PROGRAMS DURING PRODUCTION^{a,b}
(current dollars in millions)

Program	Planning Estimate (& Date of Data)	Development Estimate (& Date of Data)	Cost Growth at Development $\frac{c(d)}{x_i}$	1st Reported Program FY of Production		2nd Reported Program FY of Production		3rd Reported Program FY of Production		4th Reported Program FY of Production	
				Current Estimate (& Date of Data)	Cost Growth ^c $\frac{x(1)}{x_i}$	Current Estimate $\frac{c(2)}{c_i}$	Cost Growth ^c $\frac{x(2)}{x_i}$	Current Estimate $\frac{c(3)}{c_i}$	Cost Growth ^c $\frac{x(3)}{x_i}$	Current Estimate $\frac{c(4)}{c_i}$	Cost Growth ^c $\frac{x(4)}{x_i}$
SHILLELAGH	\$ --d	\$ 373	(6/69)	\$ --	(6/69)	\$ --	\$ --	\$ 573	\$ 200	\$ 521	\$ 148
P-3C	--d	1,294	(6/69)	2,262	(6/69)	2,610	1,316	2,426	1,132	2,527	1,233
BQ-2	127	179	(6/69)	--	(6/69)	--	--	270	143	299	172
EA-6B	690	818	(6/69)	1,035	(6/69)	1,090	400	1,154	464	1,659	969
STANDARD ARM	180	242	(6/69)	--	(6/69)	--	--	251	71	228	48
SQ-23	160	176	(6/69)	322	(6/69)	393	223	235	75	172	12
A-7E	--d	1,466	(6/69)	--	(6/69)	--	--	200	752	2,931	1,465
MINUTEMAN II	2,873	4,164	(6/69)	1,919	(6/69)	1,666	200	2,218	752	2,931	1,465
MINUTEMAN III	2,678	4,339	(6/69)	4,281	(6/69)	5,049	2,176	5,376	2,503	5,397	2,524
TITAN III	932	746	(6/69)	4,225	(6/69)	5,998	3,320	6,188	3,510	6,289	3,611
F-111	4,687	5,506	(6/69)	--	(6/69)	--	--	1,130	138	1,189	257
HMK (Improved)	336	573	(6/70)	7,401	(6/69)	7,341	2,654	7,571	2,884	7,506	2,819
M-60A2	162	203	(6/70)	812	(6/70)	847	511	771	435	773	437
TOM	410	727	(6/70)	376	(6/70)	408	246	403	241	402	240
F-2C	--d	586	(6/71)	652	(6/70)	825	415	--	--	--	--
Mark 48	582	700	(6/69)	868	(6/71)	874	288	872	286	--	--
VAST-247	241	312	(6/70)	2,246	(6/71)	1,960	1,278	1,503	821	--	--
SQS-26CX	89	96	(6/69)	445	(6/71)	435	194	--	--	--	--
				120	(6/69)	120	31	159	70	--	--
\bar{x}	\$ 323.86	\$ 727.93	\$ 946.57	\$ 727.93	\$ 946.57	\$ 861.56	\$ 1,071.92				
n	14	14	14	14	14	14	13				
p	\$1,017.64	\$1,168.14	\$1,168.14	\$1,168.14	\$1,168.14	\$1,082.19	\$1,227.54				
Weighted Average Program Cost-Growth	32%	65%	81%	65%	81%	80%	87%				
Trend Line ((u) = \bar{x}/\bar{p})											
Weighted Standard Deviation (o)	±25%	±39%	±41%	±39%	±41%	±32%	±35%				

^aSource of data: Ref. 1.

^bFor notes on method of computation and weighting, see Appendix F.

^cCost growth over earliest available estimate (planning estimate, if reported; otherwise, development estimate).

^dLack of planning estimate results from late SAR reporting requirement.

average growth of total program cost rose from 65 percent in the first reported year of production to 87 percent in the fourth year.

From Table III-3 it is thus seen that the growth of the estimated total program cost from the conceptual or planning stage to a year of stable production (or to termination) was 87 percent on the average.* A number of adjustments to the cost estimates for individual programs had usually taken place throughout the programs in attempts to bring the estimates into line with budgetary realities.

b. Cost Growth and Cost-Estimating Deficiencies. Cost growth is not a perfect indicator or measure of the success of program cost estimates, because the many changes that occur during an average program change the basis upon which the original cost estimate was made. These changes often involve weapon-system performance requirements, program schedule, and production quantity. In 1970, the SAR was amended to identify the cost effects of these alterations in program, as well as other causes for program cost change. Additional reasons given for revision of cost estimates include support item changes, economic changes, "unpredictable" changes, and "estimating" changes. The effects of each have been reported in the SAR since 1970.

The GAO has examined the causes of program cost variance by three major categories: changes in requirements, errors in estimation, and economic changes. Data from the GAO analyses for FY 1970 through FY 1972, as shown in Table III-4, indicate that changes in program scope and requirements accounted for 45 percent of the total growth in program cost in FY 1972, while estimating errors accounted for 25 percent and inflation for 30 percent. It is observed that the table indicates reductions in the percentages of total cost growth attributed to estimating errors and to changes in program and requirements during the three-year reporting period. However, the percentage of cost growth attributed to economic changes increased by 58 percent

* The weight assigned to each program was proportional to the initial estimate of total program cost. See Appendix F for details of the weighting method.

(from 19 percent in FY 1970 to 30 percent in FY 1972), preventing much improvement in total cost-estimating performance.

TABLE III-4. SUMMARY OF SAR DATA ON FPROGRAM COST GROWTH^a
(dollars in billions)

	Fiscal Year		
	1970	1971	1972
Total Number of Systems	61	77	45
Total Estimated Cost Growth	\$21.6	\$18.7	\$19.1
Cost Growth Due to Economic Changes	\$ 4.0	\$ 4.2	\$ 5.7
Percentage of Total Cost Growth	19%	22%	30%
Cost Growth Due to Estimating Errors	\$ 6.2	\$ 5.5	\$ 4.8
Percentage of Total Cost Growth	29%	29%	25%
Cost Growth Due to Changes in Program & Requirements	\$11.4	\$ 9.0	\$ 8.6
Percentage of Total Cost Growth	52%	49%	45%

^aSource: Ref. 1.

c. Cost Growth in Electronics Acquisition. While cost experience with major weapons systems has been documented through the project reporting systems, comparable data on the program costs of electronic equipment and subsystems have not been extensively documented and analyzed. One of the few studies of program cost experience in electronics has been a study by the Army Procurement Research Office² in which 193 electronics prime contracts were analyzed as part of a total statistical sample of 740 contracts for all types of Army commodities.

The results of the Army study show that electronics contracts have experienced cost growth comparable to that of major weapons systems. The data indicate that much of the documented growth can be attributed to changes in contract content or scope. Table III-5 summarizes the cost growth in electronics contracts documented by the Army study.

TABLE III-5. COST GROWTH IN ARMY ACQUISITIONS OF ELECTRONICS AND ALL TYPES OF COMMODITIES^a

<u>Commodity</u>	<u>Research & Development</u>		<u>Procurement</u>		<u>Total Acquisition Program</u>	
	<u>Number of Contracts</u>	<u>% Cost Growth</u>	<u>Number of Contracts</u>	<u>% Cost Growth</u>	<u>Number of Contracts</u>	<u>% Cost Growth</u>
Electronics	68	165% ^b	125	137% ^c	193	147% ^d
All Types	236	257%	504	108%	740	156%

^aSource: Ref. 2

^bStandard deviation 287%.

^cStandard deviation 306%.

^dStandard deviation 229%.

Although the statistics available on electronics cost growth are sparse, evidence documented to date supports the belief that acquisition of electronic equipment and subsystems is subject to the same cost uncertainties as acquisition of major weapons systems and possibly to some additional cost uncertainties caused by rapid advances in electronics technology. Thus, the cost growth of electronics resulting from uncertainties in estimating the scope of work, varying economic conditions, and changing requirements is not less than the cost growth of major weapons systems. The average cost growth of major systems at the completion of development and production is contained within the uncertainty bandwidth of the Army's estimates (Table III-5) for electronics.

d. Cost Growth and Uncertainty in Cost Estimation. The concept of cost-estimating uncertainty and realized program cost experience can be explored quantitatively if estimating uncertainty is defined to include uncertainty in all the factors that will ultimately influence the total program cost. Cost growth data then become an empirical

measure of documented ability to estimate ultimate program cost at periodic stages in a program.

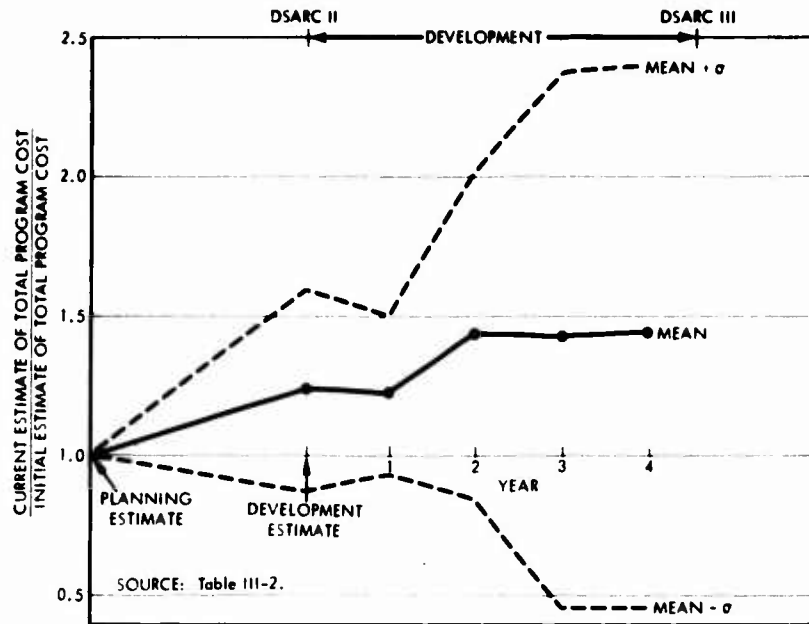
To illustrate the uncertainty in estimates for major weapons systems, cost data reported by the SARs and the GAO have been analyzed. As shown in Fig. III-1, covering development, the ratio of the current estimate to the initial estimate of total program cost starts from unity (zero uncertainty) at the planning stage and becomes 1.43 ± 0.96 at DSARC III. For the programs that go on to production (Fig. III-2), this ratio is 1.87 ± 0.35 at the fourth year of production (or termination).

The demonstrated uncertainties in estimating future program costs agree with studies by the Rand Corporation that show the estimating uncertainty associated with equipment cost estimates to be of the order of 20 to 25 percent about the mean estimate. Rand also indicates that the estimated operating cost of avionics can be expected to increase by a factor of 10 between DSARC II and DSARC III.³ Using the life-cycle cost model of the Air Force Logistics Command and program cost data on the Litton N-16 inertial platform, Rand demonstrates that predictions of program 10-year support cost increased from \$14.7 million to \$131.6 million between DSARC II and DSARC III, and that the standard deviation about the mean decreased from 25 percent to 19 percent (Table III-6).

TABLE III-6. 10-YEAR SUPPORT-COST ESTIMATES AND UNCERTAINTIES, LITTON N-16 INERTIAL PLATFORM^a
(dollars in millions)

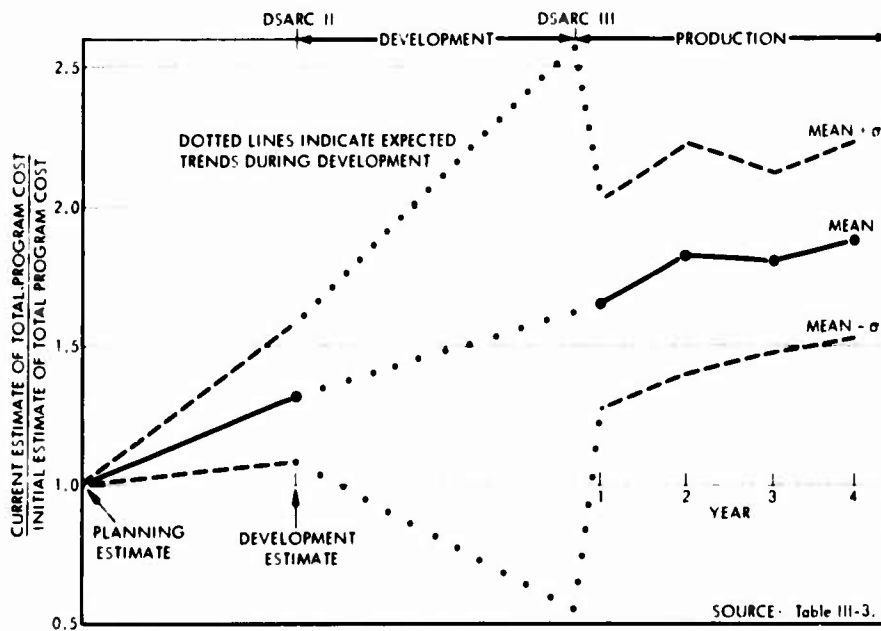
	<u>At Initiation of Development</u>	<u>Well into OT&E</u>
Estimate	\$14.727 \pm 3.750	\$131.565 \pm 25.515
Standard Deviation	$\pm 25\%$	$\pm 19\%$

^aSource: Ref. 3.



5-14-74-2

FIGURE III-1. Ratio of Current Estimate of Total Program Cost During Development to Initial Estimate of Total Program Cost



5-14-74-3

FIGURE III-2. Ratio of Current Estimate of Total Program Cost During Production to Initial Estimate of Total Program Cost

The significance of these and similar parallel studies is that empirical cost experience, both with major weapons systems and with electronic subsystems, clearly demonstrates that early cost estimates have been uniformly understated and, while the uncertainty surrounding the estimate improved in absolute value as the programs proceeded into production, unexpected cost growth and the attendant estimating uncertainties have continued even throughout later stages of the production process.

The implications of these empirical and theoretical analyses are critically important in the cost-constrained acquisition and deployment of weapons systems. If weapons systems must be developed and produced to a fixed unit cost, and if life-cycle costs must be held to limits compatible with overall force-mix budgets, then an estimating methodology and resultant cost estimates must be developed that will better predict ultimate program cost.

2. Cost Categories and Cost Elements

Two sources of uncertainty in electronics costs are (1) difficulties in determining the full costs to be assigned to electronic systems, subsystems, and equipments and (2) the impossibility of comparing either aggregate or ingredient costs of similar systems. The cause of these difficulties is traceable to the assignment of costs to inconsistent or noncomparable cost categories.

Recognition of these problems became widespread during the late 1960s, when comparable cost data on major weapons systems could not be obtained for use in cost-benefit studies or systems analyses. As a result, standard contract work breakdown structures (WBSS) were promulgated in MIL STD 881, and a standardized cost reporting system based on the Cost Information Report (CIR) was established by OSD. Since then, additional guidance has been furnished by the Service procurement commands, and additional cost reporting systems have been created to supersede and supplement the CIR system. In 1973, the most comprehensive cost data reporting system to date, based on the Contractor Cost Data Report (CCDR), was proposed. Standard cost

categories, as shown in Table III-7, were also established, linking the life-cycle phases, appropriation categories, and work breakdown elements to weapon-system cost definitions.

TABLE III-7. JOINT LOGISTICS COMMANDERS' COST-DEFINITION STRUCTURE

Terminology	Life-Cycle Phases					Appropriations			Work Breakdown			
	Concept	Validation	Engineering Development	Production	Operation	R&D	Procurement	Military Construction	Other	Weapon System	Support	Other
Development												
Flyaway (Production) Cost ^a												
Weapon-System Cost ^a												
Procurement Cost ^a												
Program Acquisition Cost ^a												
Life-Cycle Cost												

^aDefinition same as in DOD Budget Guidance Manual.

Despite these attempts to organize and record the costs incurred during weapon-system acquisition, the cost elements and cost categories do not always provide the level of detail or the focus needed to ascertain costs peculiar to electronics. Thus, while MIL STD 881 specifies a structure for an electronic-system work breakdown, as shown in Table III-8, the definition of electronic system in MIL STD 881 excludes electronics "peculiar to or closely identified with" another type of system. Electronic subsystems or components are therefore often submerged in weapon-system WBSs, and their costs are not reported in detail.

Even when electronics represents a major system or equipment that can be assigned to a Level 1 WBS (Table III-8), costs incurred during acquisition may be variously categorized. The terms "hardware cost," "flyaway cost," "production cost," "weapon-system cost," and "procurement cost" all have similar connotations, but, as Table III-7 suggests, the costs associated with these categories can vary widely in content. The fact that this source of ambiguity persists will be demonstrated when the specified cost to be "designed to" in the electronics design-to-cost experiments is discussed in Section III-C-4.

TABLE III-8. SUMMARY WORK BREAKDOWN STRUCTURE: ELECTRONIC SYSTEMS^a

<u>Level 1</u>	<u>Level 2</u>	<u>Level 3</u>
Electronic System	Prime Mission Product	Integration & Assembly/Sensors/Communications/Automatic Data Processing Equipment/Computer Programs/Data Displays/Auxiliary Equipment
	Training	Equipment/Services/Facilities
	Peculiar Support Equipment	Organizational-Intermediate (Including Equipment Common to Depot)/Depot (Only)
	Systems Test and Evaluation	Development Tests/Technical Evaluation/Operational Evaluation/Mockups/Test & Evaluation Support/Test Facilities
	System/Project Management	Systems Engineering Management-Systems Engineering/Supporting Project Management Activities
	Data	Technical Orders & Manuals/Engineering Data/Management Data/Data Depository
	Operational/Site Activation	Contractor Technical Support/Site Construction/Ship-Vehicle Conversion/System Assembly, Installation, and Checkout on Site
	Common Support Equipment	Organizational-Intermediate (Including Equipment Common to Depot)/Depot (Only)
	Industrial Facilities	Construction-Conversion-Expansion/Equipment Acquisition or Modernization/Maintenance
	Initial Spares & Repair Parts	(Specify by allowance list, grouping, or hardware element.)

^aSource: MIL STD 881.

The retrieval of cost data describing all the costs expended or allocated to an electronic system either during acquisition (RDT&E and Investment) or over the system life cycle has been hindered by the inconsistency and unavailability of comparable cost-element data. As discussed in Appendix B, in-house expenditures totaling \$5.4 billion are estimated for Government support of electronic equipment in the appropriations categories of research and development, procurement, and operations and maintenance during FY 1974. But, although these expenditures represent approximately 40 percent of the total Government electronics expenditures, there is no set of cost elements and assigned costs that can be compared to the cost information available from industrial contractors. For example, the indirect cost categories specified for contractor reporting under the CCDR format include the 12 indirect cost categories shown in Table III-9. Nowhere are Government indirect costs allocated to specific weapons systems or contractual efforts at the same level of detail so that the full costs of acquisition and operations can be determined.

3. Cost Reporting Systems

A second major area contributing to uncertainty in measurement of the costs of electronic systems and equipment is that of cost reporting systems. Augmenting the contract and program financial records of a procurement or project, cost reports are designed to furnish the DOD decisionmaker with data on product and program costs necessary to ascertain a project's financial status and to anticipate its future costs. These reports are also to serve as historical records of the actual costs incurred during the program.

An examination of the major reporting systems within the DOD reveals that, until the creation of the Contractor Cost Data Report (CCDR), major gaps existed in the coverage of the standard reporting system during systems and equipment acquisition. As shown in

TABLE III-9. SUMMARY OF INDIRECT COST CATEGORIES

- | | |
|---|---|
| <p>a. <u>Indirect Labor</u></p> <ul style="list-style-type: none"> (1) Salaries/Wages (2) Supplemental Allowances (3) Apprentice and OJT (4) Administrative and Supervision (5) Other <p>b. <u>Employee Benefits</u></p> <ul style="list-style-type: none"> (1) Paid Absences (2) Employee Insurance (3) Savings--Retirement Plans (4) Education (5) Other Benefits <p>c. <u>Payroll Taxes</u></p> <ul style="list-style-type: none"> (1) FICA (2) Federal and State Unemployment (3) Composite Payroll Taxes (4) Other <p>d. <u>Employment</u></p> <ul style="list-style-type: none"> (1) Employment Advertising (2) Recruitment Travel (3) Employee Relocation (4) Composite Employment (5) Other <p>e. <u>Communication/Travel</u></p> <ul style="list-style-type: none"> (1) Telephone and Telegraph (2) Postage (3) Travel (4) Corporate Aircraft (5) Other <p>f. <u>Production Related</u></p> <ul style="list-style-type: none"> (1) Expendable Tools and Equipment (2) Freight (3) Material Handling (4) Manufacturing Supplies/Services (5) Product Servicing (6) Tool Handling (7) Medical Services (8) Other | <p>g. <u>Facilities--Building/Land</u></p> <ul style="list-style-type: none"> (1) Depreciation and Amortization (2) Rentals (3) Maintenance (4) Insurance (5) Utilities (6) Property Taxes (7) Plant Rearrangement (8) Plant Security (9) Other <p>h. <u>Facilities--Furniture/Equipment</u></p> <ul style="list-style-type: none"> (1) Depreciation and Amortization (2) Rentals (3) Maintenance (4) Data Processing Services (5) Other <p>i. <u>Administration</u></p> <ul style="list-style-type: none"> (1) Office Supplies (2) Reproduction/Engineering Supplies (3) Professional Services (4) Contributions (5) Other Taxes (6) Dues, Memberships and Subscriptions (7) Conventions and Meetings (8) Office Services (9) Other <p>j. <u>Future Business</u></p> <ul style="list-style-type: none"> (1) Bid and Proposal (2) Independent Research and Development (3) Advertising (4) Other Promotions <p>k. <u>Other Miscellaneous</u></p> <ul style="list-style-type: none"> (1) Assessments and Transfers (2) Employee Awards (3) Corporate Allocations (4) Patents and Royalties (5) Other <p>l. <u>Credits</u></p> <ul style="list-style-type: none"> (1) Services to other Divisions (2) Cash Discounts (3) Other Credits |
|---|---|

Table III-10, coverage of maintenance costs is quite incomplete, despite Service attempts to comply with DOD directives for uniform cost accounting. Thus, the generalized finding is that the full costs of acquisition and maintenance are inadequately reported by the existing reporting systems. That is, a "single-thread" analysis by weapon system or equipment of full life-cycle cost is not presently possible by using the reported information.

The stipulation that the required information be reported is probably inadequate, as the present contract data demonstrate. Even when detailed reporting systems are imposed, the data that are collected have often been found to be incomplete, inconsistent, and ambiguous. As a recent study of naval avionics cost data concluded, the data collection system for contract costs did not provide an adequate basis for cost analysis or cost prediction, despite the fact that the contractual records were the most detailed and comprehensive records available.⁴

Therefore, it is insufficient just to design and promulgate a system directing that the proper costs be recorded. Such a system must be subjected to periodic validation or self-checking to ensure that its output is valid and comparable. Equally important, the data produced by such a reporting system must be catalogued, stored, and made accessible to the cost analysis community.

a. Finding. Throughout the Electronics-X Study, we have encountered a profound lack of valid cost data and overwhelming inadequacies in the pertinent reporting systems. More specifically:

- DOD appears to have no cost accounting system capable of providing data on the full life-cycle costs of any electronic subsystem. Full life-cycle costs include RDT&E, Procurement, O&M, Military Personnel costs, other direct costs, allocable indirect costs, and depreciation or other measure of capital investment in support equipment and facilities. Maintenance costs and indirect

TABLE III-10. CONTENT OF SELECTED DOD COST REPORTING SYSTEMS APPLICABLE TO ELECTRONIC SYSTEMS AND EQUIPMENT

Selected DOD Cost Reporting System	Budget Appropriation Sector	Research & Development				Procurement				Operations and Maintenance			
		Government		Industry		Government		Industry		Government		Industry	
		Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
1. Cost Information Report (CIR)				x	x			x	x				
2. Selected Acquisition Report (SAR)	x			x	x	x		x	x				
3. Procurement Information Report (PIR)								x	x				
4. Contractor Cost Data Report (CCDR)	x		x	x	x	x	x	x	x				
5. Cost Performance Report (CPR)				x	x			x	x				
6. Contract Funds Status Report (CFSR)				x	x			x	x				
7. Uniform Maintenance Cost Accounting and Production Reporting System (911) (USA) ^a										x	x	b	b
8. Aircraft Maintenance Cost Summary (USN) ^a MSO 4790, A2391-04										x			
9. Depot Maintenance Management Summaries ^a (USAF)										x	x	x	x

^a Depot maintenance cost only

^b Only total costs are known

costs, in particular, are very inadequately known from a cost accounting point of view. Moreover, there is often confusion as to the significance of the various reported costs because of inadequate or nonuniform definition of cost elements. As a result, cost estimation and cost-effectiveness tradeoffs are difficult at best and often impossible.

b. Recommendations

- ★★★ A systematic effort should be undertaken to develop a stepwise implementation of a complete and uniform cost accounting system throughout DOD, with emphasis on valid input data. This system must be compatible with the cost accounting system for DOD contractors that is evolving under the aegis of the Cost Accounting Standards Board. It must allow meaningful comparison between Service in-house costs and contractor costs on individual systems, subsystems, and equipments. As a first step, a marginal cost system using sampling techniques for support-cost inputs should be implemented. The system must then evolve to cover full costs of both acquisition and support.
- ★★ A central organization within OSD should be designated to organize this cost information system and to coordinate the efforts of responsible Service elements.
- ★ To test and exercise the system, each Service major procurement command should designate certain electronic systems for review of cost reporting requirements. Appropriate steps should be taken to ensure consistency among the report outputs, complete record retrieval,

★★★ Highest priority; ★★ high priority; ★ priority.

and periodic validation of the reported costs. These records should be centrally located and should be made available to the cost analysis community.

4. Schedule-Estimating Uncertainties

The demonstrated inability of both Government and industry to estimate reliability and costs is matched by an inability to estimate development and production program schedules. For electronics, this is a critical concern, since many electronic equipments or systems become critical subsystems of integrated weapons systems. Optimistic scheduling at the subsystem level can result in severe disruptions in schedule at the system level, with attendant cost-growth consequences.

Schedule-estimating uncertainties can also have a significant impact upon the success of the design-to-cost concept. The production cost for a newly developed system will be sensitive to the expected date of initial production as well as the expected production rate. The initial production schedule will, of course, be heavily dependent upon the scheduling of the successful completion of the final development test program or prototype demonstration phase. Schedules, as well as costs, must be estimated realistically if the design-to-cost concept is to be viable. (See Section III-C.)

The experience of the last 15 years, however, does not provide an encouraging picture. As shown in Table III-11, several investigators have found that original development program schedules have grown by averages of 33 to 61 percent.

A GAO study¹ separated data on weapon-system schedule growth into five commodity groups: aircraft, missiles, ships, electronics,

*** Highest priority; ** high priority; * priority.

and vehicles and ordnance. This study demonstrated that, for the sample of weapons studied, electronic equipment achieved the highest average schedule growth of all five commodities, with a 56 percent growth factor during development (Fig. III-3). If the GAO data are representative of the overall schedule-estimating capability for electronic equipment, this is a significant problem area.

TABLE III-11. SCHEDULE GROWTH EXPERIENCE: DEVELOPMENT

<u>Investigator(s)</u>	<u>Number of Systems</u>	<u>Percentage Schedule Growth</u>
Peck and Scherer ⁵	12	36%
Scherer ⁶	12	60%
GAO (1970) ¹	50	33%
Rand Corp. ⁷	10	40%
GAO (1972) ¹	49	34%
IDA ⁸	50	61%

An investigation made by the Electronics-X Study team into the area of schedule estimating revealed that major program schedules commonly have not been derived from comprehensive program planning but have been determined from larger program timetables, force-planning considerations, budgetary funding factors, and political decisionmaking. It was also found that, with the exception of the PERT network methodology, development of estimating tools was virtually nonexistent. Much work remains to be done in this area.

a. Findings

- Schedule growth has been as pervasive as cost growth during the recent past.
- The causes for schedule growth were also investigated, and the following were found to be influencing factors:

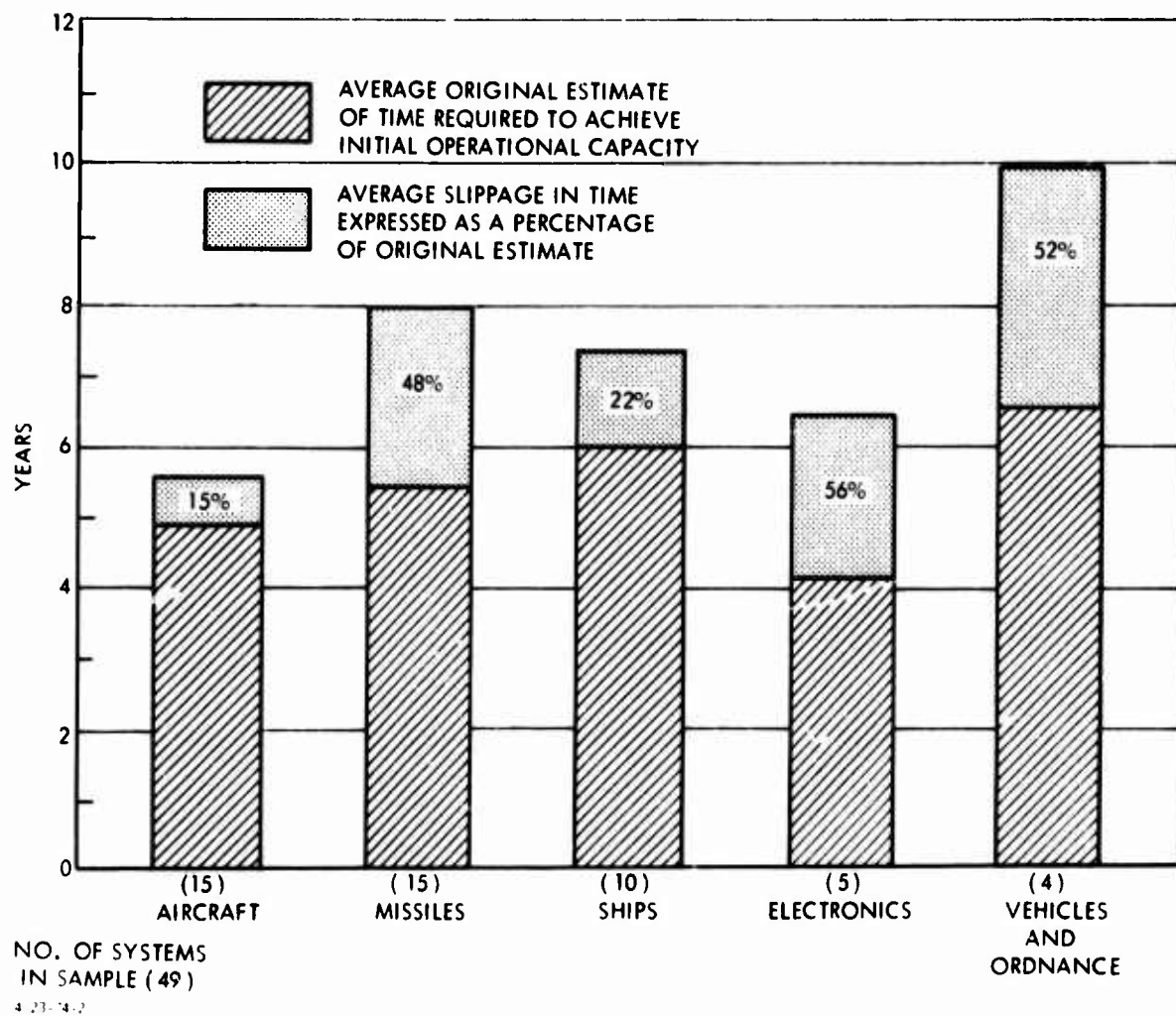


FIGURE III-3. Schedule Slippage in Five Weapon-System Groups
(Source: Ref. 1, July 17, 1972)

- Inadequate program definition
- Problems of interface with Government-furnished equipment
- Optimistic test programming
- Delays in delivery by subcontractors/vendors
- Changes in product configuration
- Delays and stretchouts of incremental funding
- Delays in program initiation
- Delays in Government approvals.

Optimistic programming and failure to plan for development problems have influenced scheduling estimates in much the same manner as they have influenced cost estimates.

- Unlike the cost-growth problem, little attempt has been made to improve existing data bases and estimating methodologies or to recognize bias by detailed verification of schedule estimates.
- Despite the rather good availability of historical data on schedules, little serious analytical work on estimating schedules has been done to date. Schedule estimation for electronics is a prime example of an area where a small effort could yield important cost savings and improved program planning.

b. Recommendations. At least three immediate steps can be taken to improve schedule-estimating capability:

- (1) Link schedule-estimating efforts to cost-estimating efforts to emphasize their interrelationships, and provide for an increased data base from past experience.
- (2) Continue to develop schedule-estimating methodology for R&D and production of electronic equipment.
- (3) Analyze schedule estimates as carefully as cost estimates in design-to-cost electronics acquisition.

5. Uncertainties in Reliability

In the following paragraphs, we shall discuss several major shortcomings in specification, measurement, and reporting of the reliability, availability, and maintainability (RAM) of electronic subsystems, and we shall also discuss shortcomings in the resulting corrective actions. We shall conclude with a few recommendations whose implementation is likely to lead to substantial improvements in the RAM of electronics.

a. RAM Requirements, Criteria, and Specifications. As some case studies cited in Section III-B suggest and as numerous discussions with industry executives confirm, RAM requirements are usually the result of guesswork, reasoning by analogy with other only vaguely similar equipment, or attempts to push the art ahead. Very rarely is a RAM requirement the result of mission analysis and cost-benefit tradeoff. Often, a RAM requirement is unattainable at a reasonable cost in equipment of the expected complexity (Fig. II-5, p. 59). The same is often true for some of the other requirements of a system, but the generally poor understanding of the significance, measurement, and cost of RAM makes it very difficult for formulators of requirements to make the tradeoff between high RAM at a high acquisition cost on the one hand and low RAM at a high maintenance cost on the other. The resulting RAM requirement usually contributes heavily to the high cost of military electronics.

In order to have a rational basis for RAM specifications, it is essential to know the nature of each phase of the mission of a system, including the mission's duration and operational environment. It is also necessary to determine what constitutes satisfactory operation during each phase of the mission and what reliability is practically attainable at affordable cost in equipment of the planned complexity. The maintenance concept must be spelled out, and the quality of maintenance available must be foreseen. Such a procedure is, in fact, followed by the National Aeronautics and Space Administration (NASA) and is largely responsible for the excellent RAM results

obtained by that organization, although at a very high acquisition cost.

Unlike NASA systems, military systems are usually intended to operate in a broad range of mission envelopes. Moreover, the real military operating environment, including quality of maintenance, is rarely, if ever, anticipated by formulators of requirements for military systems. Their lack of foreknowledge of the actual maintenance environment can be traced, in part, to the fact that changes affecting maintenance are usually not reported back to the manufacturers or to the procuring commands in a way that would enable design engineers to acquire a correct understanding of the maintenance problem.⁹ Further, the multilevel approval process contributes to a strong preference for use of RAM criteria that have a simple intuitive meaning and can be explained to many levels of management. Thus, RAM requirements have come to be stated and discussed in terms of mean time between failures (MTBF), mean time to repair (MTTR), and other quantities derived from these. These concepts are valid only under certain restrictive assumptions. The usual definition of the required maintenance method and the usual description of the operating environment are quite inadequate to ensure the validity of the MTBF concept, however. Test plans are usually drawn to demonstrate the performance of a system under standardized test conditions that resemble neither the operational environment nor the effects of operational maintenance on the system. When the system is fielded, its performance is usually communicated in terms of simple but not too meaningful parameters, namely, MTBF and maintenance man-hours per maintenance action, without an adequate description of the actual operating environment or the actual quality of the maintenance. Sometimes field reliability is reported in terms of mean flight hours between failures (MFHBF), a quantity that does not necessarily have a simple relationship to MTBF and MTTR. The results give an incomplete and inaccurate picture of the reliability of military systems, and that picture then serves as a basis for future management judgments. This often leads to the formulation of more elaborate and more demanding RAM requirements.

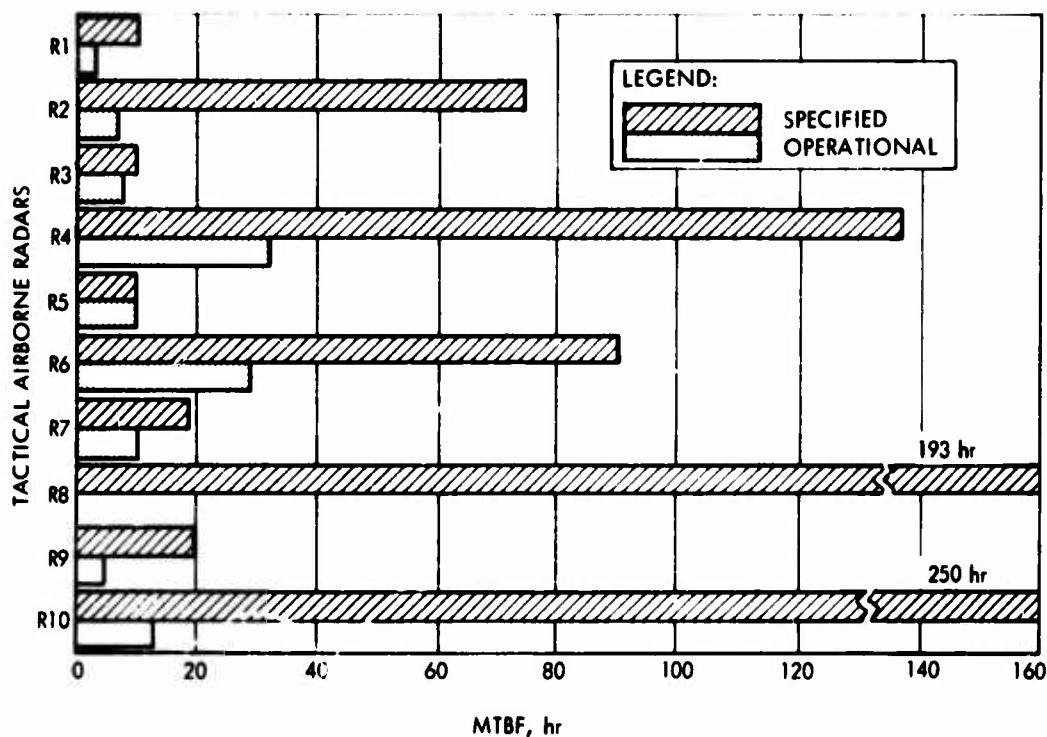
A vicious circle is thus completed, leading to overspecified and under-achieved RAM while contributing heavily to the high cost of electronic systems.

The chart in Fig. III-4 has often been used to show the inadequacy of tactical airborne radars by comparing specified MTBFs with actual MTBFs. Completely absent from the chart are a number of important pieces of information essential to a complete description of the problem. The fact is hidden that 20 to 50 percent of the avionics equipments removed and recorded as failures are later found to be in satisfactory, well-functioning condition (30 to 50 percent was estimated as typical in the airline industry by W. Carnes, Arinc; a 20 percent figure was found from 1970-71 data on noncombat squadrons of F-4J, A-7E, and A-6A aircraft, as reported by the Navy's Maintenance and Material Management (3M) systems;* a figure of 30 percent for cabin-pressure controllers was reported by H.W. Adams and H. Boyer at the 6th Annual FAA International Symposium, 8 December 1970; and 40 percent was the figure found by AFLC for the Litton N-16 inertial platform well into the OT&E phase³). Thus, the true field MTBF of avionics may be expected to be higher by a factor of 1.5 to 2 than the reported field MTBF because of no-fault removals. Similar factors may be expected in other electronics.

On a more fundamental level, the use of MTBF implicitly assumes that all failures are alike and that every repair action brings the equipment back to like-new condition. Both of these assumptions are generally untrue. It also assumes that failures are

*These no-fault figures include organizational and intermediate levels only. No figures are quoted for no-faults discovered at depots. Depots operate on a batch-processing basis. By the time an equipment has been returned to a depot, most of the expenditures (e.g., expenditures for paperwork, removal and replacement, and transportation) entailed in the repair cycle have already been made. Thus, in most cases, it makes no sense to spend much effort to determine whether a subsystem is working, which may mean that it still has about 50 percent of its useful life ahead. It is more economical to go ahead with a complete overhaul to restore the equipment to like-new condition.

indeed correctly attributed to the faulty electronic subsystems; this assumption is often wrong.¹⁰ While these facts can have a large effect (possibly as much as a factor of 20) on the apparent field MTBF, quantification is most difficult indeed, and generalization from one equipment to another may be unwarranted.



11-14-73-6

FIGURE III-4. Specified and Actual MTBFs of Tactical Airborne Radars

The use of MTBF also obscures the fact that failures of equipment usually come in clusters, and that often this can be traced to poorly trained maintenance personnel who tend either to repair equipment inadequately after the first failure or to remove well-functioning equipment without sufficient cause. In a study of a sample of AN/AWC-10 fire-control radars, Westinghouse observed a field MTBF

of 7.5 hours. Then, when experienced technicians servicing these radars were replaced by neophytes, the MTBF of the very same sample of radars under the very same operating conditions suddenly dropped to 3.8 hours, down by a factor of 2. This, of course, is nothing surprising. It is a typical learning-curve effect. It simply shows the inadequacy of MTBF alone as a measure of field RAM, since MTBF can easily vary by a substantial factor because of an unreported circumstance such as a change in the degree of experience of the maintenance force.

Let us discuss the connection between specified MTBF and field MTBF in somewhat greater detail. There exists an inherent MTBF typical of in-plant test conditions, where all pertinent parameters are adequately controlled. When equipment is taken into the operational environment, certain new, unpredictable effects begin to show up, many of which are directly caused by human failings. Thus, every "inherent" equipment failure that necessitates a maintenance action exposes equipment to the possibility of suffering another maintenance-induced failure. Such failures often occur because maintenance actions under field conditions expose equipment to various kinds of direct damage by inexperienced maintenance personnel, such as short-circuiting by wrong use of test leads and breakage by dropping.

Failures of electronics are also caused by human abuse. For example, a communication set was tested in a plant and found acceptable. Then it was installed in a tank, where the gunner used it as a stepladder and broke off its protruding knobs. This was a failure that could not have been readily foreseen on the basis of in-plant tests but might have been avoided by human-factors engineers with sufficient field experience.

Still other "failures" are apparent only. Such "failures" are often charged to a subsystem by a Service maintenance data collection system even though they entail only unnecessary maintenance. A case in point is the unnecessarily frequent calibration of a Singer-Kearfott AN/ASN-90 inertial navigation unit that was improperly

charged against the unit by the Air Force AFM 66-1 reporting system.¹⁰ All these failures become part and parcel of the "field MTBF" that is now used as a measure of the field performance of an electronic subsystem.

To summarize:

1. RAM requirements and specifications must be based on the best possible mission analysis, taking into account the range of missions planned for the system and the realizability of the proposed RAM specifications in an equipment of the proposed complexity and unit production cost.
2. For each phase of each mission, a suitable set of RAM parameters can be specified, measured, and reported. For example, one or more of the following parameters may be specified: MTBF, MTTR, probability of mission success, availability, effectiveness, probability of m out of n units surviving, or mean time between maintenance actions. This will entail imposing special RAM reporting requirements for each system, and methods for accomplishing this will still have to be worked out.
3. Methods must still be developed for describing quantitatively the effects of the actual use environment and the maintenance setup. This is essential in order to provide a complete RAM specification and relevant measurement techniques.

Findings and recommendations stemming from the above are presented at the end of the next section.

b. RAM Reporting Systems. Let us next review the information systems upon which we currently depend for RAM data. First, there are the readiness reporting systems. Readiness is a very important quantity militarily. Moreover, the military commander is usually rated on his readiness. Table III-12 shows that only instruments,

TABLE III-12. PERCENTAGE DISTRIBUTION OF MISSION ABORTS^a

SYSTEM	SYSTEM NAME	B-5D	B-52G	B-52H	B-58A	C-124B	C-130E (TAC)	C-130E (MAC)	EC-135A	EC-135C	C-140A	F-4C	F-15A	T-38A	F-106C	F-106D	F-111A
11	AIRFRAME	5.4	6.0	5.2	5.7	0.8	2.5	1.6		9.1	9.7	4.6	9.0	3.1	5.0	0.3	0.6
12	FUELAGE	2.7	1.8	0.5	1.4	0.8	1.0	0.4		0.0	1.0	4.2	3.0	0.4	1.4	1.5	2.1
13	LANDING GEAR	0.0	4.1	2.7	7.2	17.9	6.6	8.4		5.1	13.6	14.1	12.0	6.7	16.6	9.7	4.5
14	FLIGHT CONTROLS	5.4	4.6	2.5	8.1	4.9	4.1	3.5		0.0	23.9	7.8	6.0	3.8	15.8	13.4	13.6
22/23/24/32	PROPULSION	14.1	19.4	19.1	29.3	48.8	52.1	54.6		69.2	24.5	13.2	40.1	40.2	23.8	10.6	24.8
25	AUXILIARY POWER UNIT	N/A	N/A	N/A	N/A	2.0	1.4	1.4		5.1	0.1	N/A	N/A	N/A	N/A	N/A	N/A
41	AIR CONDITIONING/PERMANENTIZATION	2.4	1.8	1.9	9.6	3.0	0.3	5.1		0.0	2.1	7.0	0.0	2.2	1.4	2.9	3.3
42	ELECTRICAL POWER SUPPLY	20.0	12.9	21.5	8.1	5.7	3.4	6.7		0.0	1.9	7.5	9.9	5.2	8.6	7.1	3.3
44	INTERIOR/EXTENSION LIGHTING	2.7	1.4	3.8	0.0	0.0	0.0	1.4		0.0	1.0	0.6	4.0	1.2	0.0	0.2	2.1
45	HYDRAULIC/PERMANENT POWER SUPPLY	2.7	6.0	3.5	7.7	3.0	5.1	4.1		0.0	3.1	9.6	3.0	1.4	4.3	13.6	6.3
46	FUEL SUPPLY	21.4	3.2	4.4	7.3	34.6	2.7	2.4		0.0	1.0	6.6	2.0	0.7	3.6	5.5	4.8
47	EXTENS SUPPLY	2.2	2.9	1.1	0.4	2.0	0.0	0.0		0.0	0.1	3.8	2.0	1.6	0.7	0.7	0.3
49	FOUR EXTENSION	2.4	0.0	0.0	0.0	1.6	1.4	2.4		0.0	5.9	2.0	2.0	1.2	0.7	4.5	0.6
51/56	INSTRUMENTS	5.4	5.5	1.4	3.2	3.3	1.0	3.0		0.0	7.4	1.4	3.9	13.3	7.9	12.4	6.2
52/59	APPROPRIOT	0.0	0.0	0.5	2.4	N/A	2.2	1.8		0.0	2.4	1.5	4.0	0.3	N/A	4.7	11.1
61	WP COMMUNICATIONS	0.0	3.7	4.9	3.0	1.6	0.0	2.0		5.1	1.3	N/A	N/A	N/A	N/A	N/A	0.0
62	WP COMMUNICATIONS	N/A	N/A	N/A	N/A	0.0	0.0	0.4		0.0	0.0	N/A	N/A	N/A	N/A	N/A	N/A
63	WP COMMUNICATIONS	2.4	2.9	0.5	0.4	0.0	0.0	0.4		10.2	0.0	28.2	4.0	5.8	9.8	3.2	1.2
64	INTERPHONE	0.0	0.0	0.5	0.0	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
65	INTERPHONE	0.0	0.0	0.5	0.0	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
66	INTERPHONE	0.0	0.0	0.0	0.4	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
67	INTERPHONE	0.0	0.0	0.0	0.4	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
68	INTERPHONE	0.0	0.0	0.0	0.4	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
69	INTERPHONE	0.0	0.0	0.0	0.4	0.0	0.0	0.0		0.0	0.1	28.2	4.0	1.0	0.0	0.0	0.0
71	RADIO NAVIGATION	2.2	2.5	2.5	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
72	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
73	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
74	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
75	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
76	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
77	RADIO NAVIGATION	2.7	2.3	2.0	0.0	0.0	0.0	0.0		0.0	0.1	7.6	2.0	0.0	0.7	2.0	0.0
91	EMERGENCY EQUIPMENT	0.0	0.5	0.0	0.0	0.0	0.0	0.0		0.0	0.1	1.0	0.0	0.0	0.7	2.2	N/A
93	DATA CENTER	0.0	0.5	0.0	0.0	0.0	0.0	0.0		0.0	0.1	1.0	0.0	0.0	0.7	2.2	N/A
95	PERSONNEL EQUIPMENT	N/A	N/A	N/A	0.0	0.0	0.0	0.0		0.0	0.1	1.0	0.0	0.0	0.7	2.2	N/A
97	EXPLOSIVE DEVICES	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.1	1.0	0.0	0.0	0.7	2.2	N/A

NOTE: "N/A" indicates systems "Not Applicable" to the aircraft model.

Source: Field Experience Data, processed through "Abort" Program

the bombing navigation system on a bomber, and a few other electronic subsystems cause mission aborts either on the ground or in the air. Thus, while some electronic subsystem failures may contribute to a "reduced material condition," they are not really likely to be discussed in a readiness report in sufficient detail to allow any meaningful deduction of RAM data, nor will the listing of the Work Unit Codes (WUC) in the readiness report be sufficiently inclusive to serve as a useful catalog of the current RAM problems.

The existing sources of maintenance data are shown in Tables III-13 through III-15. Maintenance data collection systems (MDCSSs), such as the Navy's Maintenance and Material Management (3M) systems, collect data at the base level in enormous quantities, as the 2.5 million records per month of 3M-Aviation (Table III-14) show. The records are mainly intended for local management of maintenance and logistic support. They report man-hours expended and material used. Emphasis is on safety-related equipments, and consequently aviation coverage is maximized. AFM 66-1 is the largest such system, 3M-Aviation is the next largest, and The Army Maintenance Management System--Aviation (TAMMS-Aviation) is the smallest.*

RAM data is strictly a byproduct of these systems--and, one might add, a very insufficient byproduct, because essential qualifying or explanatory RAM information is often not noted. RAM data can serve as a red-flag device; for example, when fairly frequent failures are noted in the output of 3M, a detailed investigation is obviously in order. The problem is that the data from this system is usually punched into cards locally and processed for local purposes. For more elaborate processing, it is forwarded monthly to a central location. By the time it is likely to reach the producer command or the manufacturer, this data is two to three months old, and thus it is a very sluggish warning signal. Only readiness-related information is processed faster, and we have already discussed its weaknesses as a

*The Army Maintenance Management System--Sample Data Collection (TAMMS-SDC) will be discussed separately.

TABLE III-13. SOURCES OF MAINTENANCE DATA APPLICABLE TO ELECTRONICS

	<u>Service(s)</u>
A. <u>Maintenance Data Collection Systems (MDCSs), Operational</u>	
1. Aviation Maintenance & Material Management (3M-Aviation)	Navy, USMC
2. Ships Maintenance & Material Management (3M-Ships)	Navy
3. Maintenance Data Collection System (AFM 66-1)	USAF
4. The Army Maintenance Management System--Aviation (TAMMS-Aviation)	Army Aviation
5. The Army Maintenance Management System--Sample Data Collection (TAMMS-SDC)	Army, General
B. <u>Depot Maintenance Reports</u>	
1. Disassembly and Inspection Report (DIR)	Navy, USAF
2. Depot Data System (AFLCM 66-15)	USAF
C. <u>Exception Reports, Operational</u>	
1. Unsatisfactory Removal Report (UR/UMR)	Navy, USAF
2. Emergency Unsatisfactory Removal Report (EUR/EUMR)	All
3. Accident Report	All
4. Equipment Improvement Request (EIR)	Army
5. Engineering Investigation Request (EIR)	Navy
D. <u>Other Data Sources</u>	
1. Field Commander Message Traffic	All
2. Contractor Field Representatives	--
3. Technical Field Representatives of Producer Commands	All
E. <u>Rank-Ordering Data-Processing Systems</u>	
1. Increase Reliability of Operational Systems (IRO\$)	USAF
2. Improved Management of Procurement and Contracting Techniques (IMPACT)	Army

TABLE III-14. CHARACTERISTICS OF MAINTENANCE DATA COLLECTION SYSTEMS (MDCSS)

- Voluminous

Typical Total Numbers per Month of Reports
Including Electronics Information, millions

TAMMS-Aviation:	0.9
3M-Aviation:	2.5
3M-Ships:	0.7
AFM 66-1:	5.0

- Primary Purpose is Management of Maintenance and Logistic Support
- RAM Data is a Byproduct
- Problems in Accuracy and Completeness
- Problems in Timeliness (processed data is 2-3 months old when it reaches producer command or contractor)
- Poor Coupling of Data to Industry

TABLE III-15. CHARACTERISTICS OF EXCEPTION REPORTS

- Smaller Quantity

Typical Total Numbers per Month of Reports
Including Electronics Information

Air Force:	2000 EUMRs
Army Aviation:	1750 EIRs
Naval Aviation:	100 "Safety" URs 2500 "Special" URs 40 EIRs

- Greater Depth in Problem Description
- More Likely to Result in Direct Action

RAM feedback channel. Moreover, the maintenance data collection systems extend only to repairs at bases; they do not include repairs at depots,* where much complex electronic gear is repaired. Some data on repairs at depots is available via the depot maintenance reports (Table III-13), which, like URS (see next paragraph on exception reports), are narrative responses to specific queries and are not comprehensive information-gathering systems.

By far the most useful reports for initiating direct action are the exception reports. They provide narrative problem descriptions, and their volume is relatively small--only several thousand records per month instead of millions for the 3M or the AFM 66-1 (Table III-15). However, Service personnel are reluctant to use them unless a very clear-cut reason exists. Consequently, exception reports do not provide data about recurring, subcritical failures that might be significant as forerunners of serious trouble or as opportunities for eliminating frequent minor failures. Thus, exception reports are not routine RAM reporting systems. Furthermore, they, too, rely on the judgment of the men on the spot, and often the men on the spot are inadequately trained repairmen.

Critical problems are usually reported by Field Commander Message Traffic and do get high-level attention rapidly, but Field Commander Message Traffic is a limited, special-purpose system.

Certain other information channels exist, including reports of contractors' technical field representatives, accident reports, and incident reports. Each of these kinds of report provides data in a different format. Among them, the reports of contractors' field representatives are usually the most helpful to manufacturers and to producer commands in pinpointing specific RAM problems and in helping to obtain definitive solutions. The point is that a contractors' field representative is technically trained, is familiar with the equipment, knows what to look for, knows to some extent the conditions

*See footnote on p. 101.

under which the equipment has been used or serviced, and is motivated to report, particularly if the equipment is under warranty.

Certain military producer commands have their own technical field representatives. Examples are the Air Force Engineering Technical Service (AFETS), which reports to various Air Force commands, the Naval Aviation Engineering Service Unit under the Assistant Commander for Logistics/Fleet Support, Naval Air Systems Command Headquarters (NAIR-04), and the Technical Assistance and New Equipment Training Division, Army Electronics Command (AECOM). In fact, AECOM maintains one technical representative per \$2 million to \$6 million of new equipment that it is fielding at any one time (or one technical representative per \$20 million of the AECOM weapons inventory). Generally, technical representatives of producer commands concentrate their efforts on defining and helping to solve the technical problems of relatively new equipments.

Coupling to industry of the data produced by the maintenance data collection systems is relatively poor. Such data is not usually distributed automatically to contractors but is available to them upon request. Unfortunately, lack of confidence in these massive maintenance data collection systems results in very few contractor requests for and little utilization of the Navy's 3M summaries or the Air Force's AFM 66-1 summaries.⁹

The Services have been trying to remedy some of the problems entailed in the huge volume of the AFM 66-1 and 3M systems by providing reports that rank the major problems according to decreasing priority. The Air Force system for doing this is IRO\$ (Table III-13), which provides a capability to rank data as to cost, safety, and availability. This capability permits the ranking of each problem in components of an Air Force weapon system at the lowest possible work-unit code level, thus making the problems visible to management at the system, subsystem, and component levels and allowing corrective actions. The IRO\$ system also provides historical logistic support data to designers and developers of new systems. While this

greatly improves the utility of the output, it does not correct the inadequacies of the inputs and the resulting data base. A somewhat different system, known as IMPACT (Table III-13), is in effect at the Army Materiel Command. Its major function is to direct the attention of management to certain selected tasks and to the progress made in accomplishing them. IMPACT also continues to depend on the existing data base.

Certain observations follow from the above. Ultimately, better ways of providing feedback of valid RAM information from the field must be developed. They must serve the need for a continuing stream of routine RAM data, and they must also provide channels for exception reports and narrative descriptions when required by the producer commands and vendors. Information must become routinely available not only from bases but also from depots. All the information streams must become compatible in format to allow the tracing of a program or a system and all its relevant costs through a life cycle. Finally, the information must be coupled automatically to the producer commands and vendors for corrective actions.

Because of the magnitude of these problems and the tremendous extent of the related information systems, changes must be made very deliberately and results will be obtained very slowly, often only after a number of years of continuing effort. To effect more rapid improvement in the cost and reliability of military electronics, and to provide better guidelines for future evolution of the various maintenance data collection systems, it is essential to develop or broaden a technical representative system for the various commands that is like the one used by AECOM, TAMMS-SDC. In the AECOM approach, a few electronic systems are selected for sampling studies. Then the AMC Logistics Data Center and AECOM prepare a Sample Data Collection Plan, outlining specific information requirements that usually include reliability, availability, maintainability (organizational-level maintenance and support-level maintenance), data portrayal requirements, sample design characteristics, resource requirements,

cost benefits, and a detailed discussion of the collection process. A Field Procedures Guide is also prepared to help implement the data collection. This document outlines in detail the degree to which the technical field representative must oversee and participate in the sample data collection process. The information received from the field is then processed, and action-oriented monthly reports and a final summary are issued. The data collection period is usually a year but it may be extended or shortened, as necessary. It has been the Army's experience that the data thus provided by experienced technical field representatives is flexible in content and format and superior in quality and accuracy. As a result, the data gets the attention of key Army and contractor personnel.

An excerpt from a typical sampling report is shown in the Annex at the end of this section.

The AECOM approach has the advantage of using members of an existing technical field organization who are already in most of the required locations for the sampling study, thus minimizing the required outlay. Recommended actions are then coupled directly to the producer command and to the vendor. Similar approaches could be undertaken by other producer commands, both in the Army and in the other Services, to provide a more reliable data base and greater flexibility in the selection of parameters appropriate for each system. The AECOM experience of having one technical representative (GS-11 or GS-12) cover somewhere between \$2 million to \$6 million worth of new equipment (i.e., equipment less than 2 years old) suggests the general order of magnitude of the staff required for this broadened kind of technical field representative function. Thus, for an acquisition budget of about \$5 billion per year of military electronics, 1000-3000 personnel would be required to provide meaningful training and technical assistance with important newly fielded equipment, to report on its usage, to diagnose its problems, and to provide an expeditious reporting system that would quickly get problems resolved that now cause enormous expense. Moreover, armed with simple guidelines, such

personnel could provide an indication of the real costs of maintenance for new equipment by sampling maintenance man-hours required for typical tasks in the field. They could also report sampled data on field reliability of equipment.

At about \$25,000 per representative (this includes benefits, retirement, and "direct" overhead), 1000-3000 representatives would cost \$25-\$75 million annually, or about 0.5-1.5 percent of the total electronics acquisition budget. The additional expenditures entailed in sampled-data collection are moderate. In the few cases of Army data-sampling plans in effect, the cost was \$60,000 or \$70,000 per AN/equipment type. The cost depends upon the information required, the geographic distribution of equipments, and the number of equipment units sampled. Judiciously used, such data sampling can be a very powerful approach, resulting in substantial savings and considerable optimization of reliability.

c. Findings

- There is no routine field-reliability reporting system in DOD that can provide meaningful feedback to producer commands and to manufacturers on the field reliability of electronic subsystems. Existing maintenance data collection systems were not originally designed for reporting reliability data, and they do not perform this function adequately. Moreover, there is considerable confusion in the terms used to describe reliability. They are first used in specifications in one context and are then employed in field reports in another context. The field-use environment and the field-maintenance environment are not adequately quantified in field reports to ensure consistent interpretation of field data. Thus, field information is ambiguous at best. This poses a difficulty in predicting and specifying reliability and in comparing the attained field reliability with the specification.

- There exists one reliability data collection system that appears to be working effectively: TAMMS-SDC, a data-sampling system used by the Army. It utilizes technically trained, experienced field service personnel to sample reliability data and certain other information according to individualized sampling plans. It thus provides a possible model for the rapid, cost-effective implementation of a data collection system for selected equipments.

d. Recommendations

- ★★★ In each major producer command (AMC, NMC, AFSC, AFLC), establish (or broaden) a system for competent technical reporting of reliability, availability, and maintainability (RAM) and marginal cost feedback information from the field on selected systems and equipments, using sampling methods. Identify in each such command a data-sampling planning organization to plan and outline in detail the sampled information to be collected and the sampling methods to be used, and designate a suitable data processing activity to process and distribute the outputs of the data-sampling system.

Prime candidates for sample-data collection are:

- Newly deployed systems during the first year of operation
 - Systems/subsystems deployed in large quantity
 - Subsystems/equipments critical for the operation of major systems or being procured as GFE for major systems.
- ★★ Organize a RAM Data Systems Task Force, representing the several Services and chaired by OSD, to study and compare the relative cost-effectiveness of a routine maintenance data collection system (such as 3M or AFM

★★★ Highest priority; ★★ high priority; ★ priority.

66-1) with a sampled-data collection system (such as TAMMS-SDC). Consider and recommend the advisability of possible courses of action such as the following:

1. Discontinue routine processing of TAMMS-Aviation, 3M, and AFM 66-1 RAM data at the national level. Replace these systems by sampled-data collection systems.
 2. Continue processing at the national level all safety-related RAM information, such as 3M-Aviation, AFM 66-1, and TAMMS-Aviation. Supplement these systems by periodic sampling studies to check and improve the information collected by the maintenance data collection systems.
 3. Extend the maintenance data collection systems to the depot level in selected cases and ensure that all cost information and RAM information is compatible in format (Single-Thread Data System) so that it can be aggregated by system.
- ★ Establish a new RAM Information Exchange Program at the electronic equipment level in a form patterned after the Government-Industry Data Exchange Program (GIDEP) (Table III-16). It should
- Provide automatic interchange of RAM data related to parts, components, equipments, subsystems, and systems utilized by the Services.
 - Have participants from Army, Navy, Air Force, NASA, Canadian Military Electronics Standards Agency (CAMESA), and numerous contractors.
 - Be chartered by Joint Logistics Commanders.
 - Provide a forum for an organized direct exchange of this information with other Services and with all interested contractors.

*** Highest priority; ** high priority; ★ priority.

TABLE III-16. GOVERNMENT-INDUSTRY DATA EXCHANGE PROGRAM (GIDEP)

Purpose:	To provide Government agencies and contractors with automatic interchange of technical data related to parts, components, and materials utilized in military and space systems.
Participants:	Army, Navy, Air Force, NASA, Canadian Military Electronics Standards Agency (CAMESA), and 300 contractors.
Technical Data Bank:	Information on parts, components, materials, manufacturing processes, calibration procedures, and related technical data.
Outputs:	Parts application reports, general technical reports on parts, contractor-generated reliability specifications, in-process parts testing activity reports, calibration procedures, and related documents.
Organization:	Chartered by Joint Logistics Commanders, and operated by the Navy (Hq, NMC).
Advisory Groups:	The Government Advisory Group and the Industry Advisory Group advise the GIDEP Program Manager.

ANNEX TO SECTION III-A

EXCERPT FROM A TYPICAL SAMPLE DATA REPORT OF THE ARMY
ELECTRONICS COMMAND

SAMPLE DATA COLLECTION PLAN

Radio Set, AN/GRC-143

FSN: 5820-926-7355

A. MATERIEL IDENTIFICATION.

Radio Set AN/GRC-143 is a general purpose, frequency modulated tactical radio set which provides duplex operation in the 4.4 to 5.0 gigahertz (GHz) frequency range with a continuous wave (cw) power output capability of 1 kilowatt minimum. The AN/GRC-143 was designed to serve as the basic radio set for extended range radio relay systems for the field Army. The radio set can be used for diffractive and tropospheric scatter modes of propagation at ranges to 100 miles when used with a suitable antenna, such as antenna group AN/TRA-37. The AN/GRC-143 Radio Set can be used in two basic configurations; single stack AN/TRC-112 and double stack AN/TRC-121 to provide diffractive and tropospheric communication over distances up to 100 miles, with teletypewriter communications up to 200 miles. It can transmit up to 24 voice channels, data or teletypewriter signals in conjunction with standard military multiplex equipments. One radio set is provided for single stack pcm terminal operation and is housed in an equipment shelter such as S-336-TRC-112. Two radio sets are provided for double stack pcm cable terminal operation and are housed in an equipment shelter S-338/TRC-121. Operational procedures of the radio sets in either of the two configurations are identical. The major components of Radio Set AN/GRC-143 are:

Transmitter, Radio T-961/GRC-143, FSN 5820-815-9720

Receiver, Radio R-1287/GRC-143, FSN 5820-935-0129

Amplifier, Radio Frequency AM-6090/GRC-143, FSN 5820-815-9710

B. OBJECTIVES.

The objectives of this Sample Data Collection Plan are to collect valid data under controlled conditions to assess logistic support, maintenance, performance effectiveness, and evaluate the initial provisioning of repair parts requirements for Radio Set AN/GRC-143 when installed as part of Radio Terminal Set AN/TRC-112 to include:

1. The effectiveness of Radio Set AN/GRC-143 in terms of reliability, availability and maintainability.
2. Assessments of component reliability, availability and maintainability for detailed engineering and product improvement considerations.
3. Comparative analysis of achieved performance characteristics under operational environments as opposed to contractor estimates, tests, and engineering predictions.
4. Determination of the adequacy of initial provisioning of repair parts list.

C. INFORMATION REQUIREMENTS.

Reliability and maintainability parameters, repair parts consumption, and availability indicators will be determined for the selected end item and selected components. Statistical and engineering analysis techniques will be used to provide realistic and meaningful products directly applicable to management aspects of the equipment system, such as maintenance, quality assurance, product improvement and supply support.

1. RELIABILITY. The following characteristics will be determined:
 - a. Mean time to first failure/replacement.
 - b. Mean time between subsequent failures/replacements.
 - c. Failure/replacement rate analysis.
2. MAINTAINABILITY. (Organizational level maintenance) The following characteristics will be calculated:

- a. Mean active repair time.
- b. Mean schedule maintenance time.
- c. Mean total (end item) time in Organizational Maintenance.

3. MAINTAINABILITY. (Support level maintenance) The following characteristics will be calculated:

- a. Distribution of man-hours to repair each selected component.
- b. Distribution of total (end item) down time.
- c. Distribution of total selected component down time in hours (days).

4. AVAILABILITY. The following determination will be made of equipment availability:

- a. Inherent availability.
- b. Achieved availability.
- c. Operational availability.

5. INITIAL PROVISIONING. Evaluation of the adequacy of initial provisioning of repair parts support.

6. DATA PORTRAYAL REQUIREMENTS.

a. Data will be displayed in a summarized manner at appropriate time intervals. Graphics will be used as applicable. The specific intervals will be determined as the characteristics of the data become apparent through analysis. A comparison of equipment performance parameters will be made for the various geographical locations designed for sampling.

b. Selected components will be evaluated and identified independently with relation to their performance characteristics in support of the end item.

D. SAMPLE DESIGN CHARACTERISTICS.

1. The actual sample sizes determined will provide at minimum a 95% confidence level with 10% precision. That is, one can be at least 95% confident that parameters estimated from this sample will not differ from the value being estimated by more than 10%. As a

minimum, the number of sets to be reported on for each of the selected locations is as follows:

<u>CONARC</u>	<u>USAREUR</u>	<u>USARPAC</u>	<u>USARAL</u>
33	20	24	2

2. The units selected for sample data collection should be representative of the spectrum of activities and the various environmental conditions within the command. This will insure a thorough and comprehensive analysis of the sets under study.

3. The estimated duration for this collection effort is one year. However, this plan or parts thereof will be terminated either prior to or subsequent to the estimated duration if analysis indicates the objectives have or have not been obtained.

SAMPLE DATA COLLECTION USAGE/FAILURE PROFILE

For illustrative purposes, a hypothetical field unit, the 61st Infantry Battalion located in CONARC, is introduced. Although the battalion is not included in the SDC Program, it is desired for management planning to apply the statistics given in the report to the ten (10) AN/GRC-143 Radio Sets in the battalion. Statistics generated for the hypothetical field unit are expected values and should be treated discreetly as such.

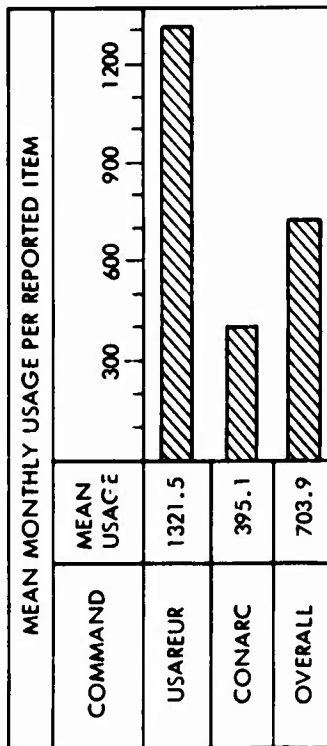


Figure III-5a displays by command the mean monthly usage in hours per AN/GRC-143 for which data was reported during the first nine months of the SDC program.

Since the 61st Infantry Battalion has a similar mission requirement as the other CONARC units with deployed sets, the materiel manager might also expect the mean monthly usage of the 61st Infantry Battalion to be 395.1 hours per set for a total battalion monthly usage of 3951 hours (number of sets deployed, 10, times the mean command usage, 395.1). The planner may also expect the newly deployed radio sets to operate 249.6 hours (the MTBF) between failures. Fourteen or fifteen failures will likely occur if usage and MTBF are as anticipated ($3951 \div 249.6$).

11-4-73-3

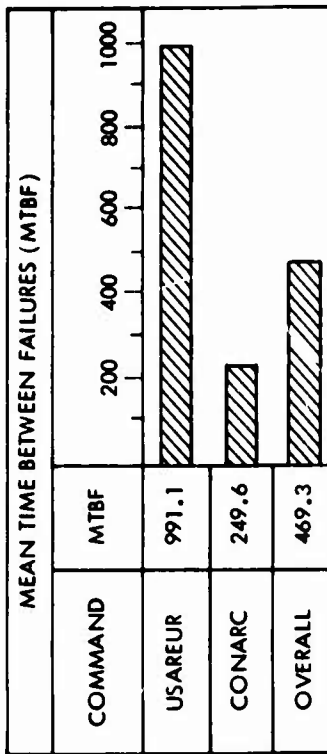


Figure III-5b shows the mean time in hours between reported failures (MTBF)

SAMPLE DATA COLLECTION

PERFORMANCE AND LOGISTIC SUPPORT CHARACTERISTICS

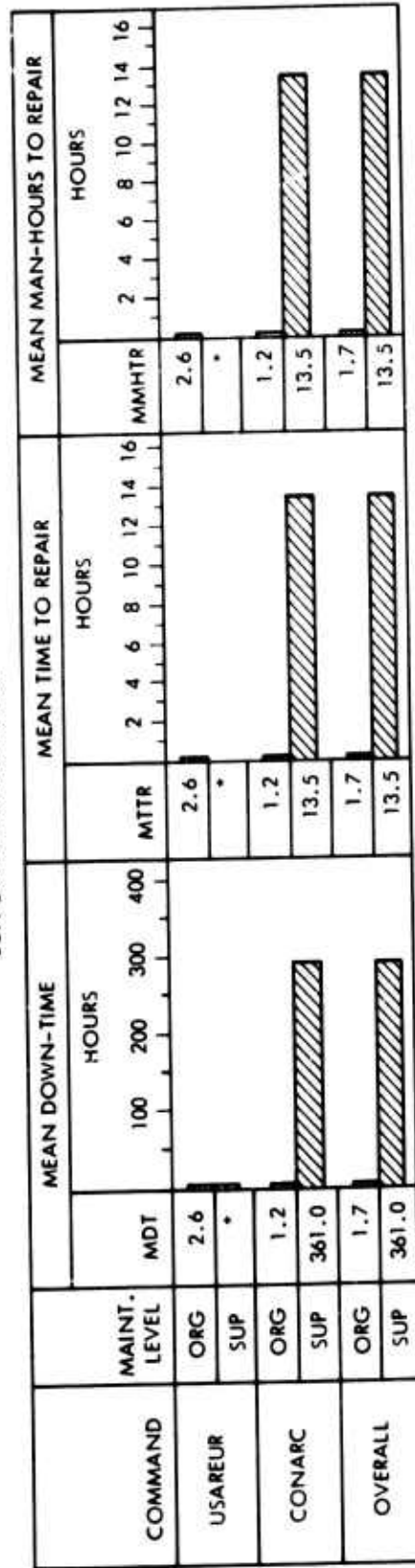


Figure 111-5c presents, by command, the mean down-time (MDT), mean time to repair (MTTR), and mean man-hours to repair (MMHTR) for both organizational and support level maintenance activities as determined by the number of incidents of each occurring during the first nine months of the AN/GRC-143 SDC program.

If a failure occurs that requires maintenance of the organizational level, the materiel manager should expect: (1) The set to be down 1.2 hours, the MDT; (2) The organizational maintenance activity to take 1.2 hours, the MTTR, to repair the set; and (3) 1.2 man-hours, the MMHTR, to be utilized to effect the repair. Should the maintenance requirement lead to a radio set being repaired by a support level maintenance activity, the materiel manager may expect: (1) the set to be down 361.0 hours; (2) the support maintenance activity to take 13.5 hours to actually repair the set; and (3) 13.5 man-hours to be utilized in effecting the repair.

*No support forms received from USAREUR.

PARTS REPLACEMENT SUMMARY

PART NOUN	PART FSN	QUANTITY REPLACED	AVERAGE TIME REPLACED (HRS)
HV INVERTER	5820 - 136 - 4965	3	1.1
AMPLAF	5820 - 135 - 4588	3	0.7
OSC RF	5820 -136 - 1233	2	1.0
FILTER	5915 - 196 - 8016	2	1.0
LAMP	6240 - 763 - 7744	2	0.2

11-14-73-5

Figure III-5d is a list of five most frequently replaced parts as reported during the first nine months of the AN/GRC-143 SDC program. Also given is the average time, in hours, which was required to replace each of the parts.

SAMPLE DATA COLLECTION

READINESS CHARACTERISTICS--AVAILABILITY

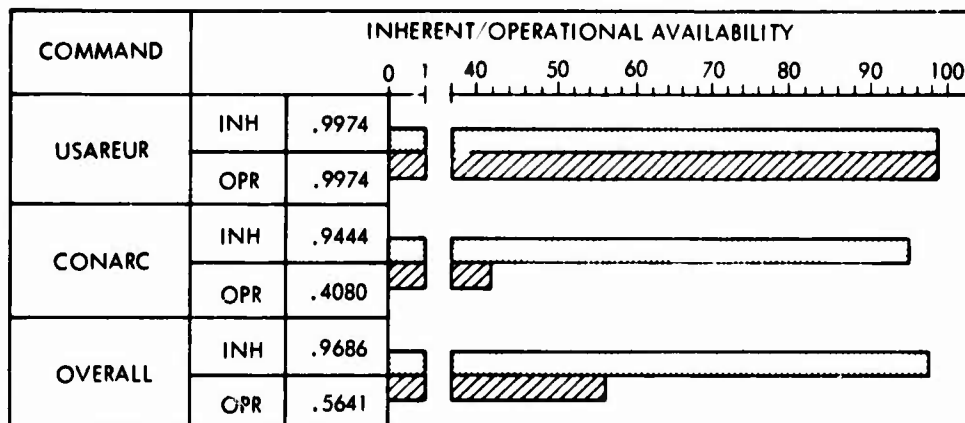


Figure III-5e compares by command area the operational and inherent availability of the AN/GRC-143 Radio Set.

Historically, the operational availability of the AN/GRC-143 Radio Sets deployed to CONARC has been .4080, or approximately 40%; the inherent availability has been .9444, or approximately 94%. Therefore, the materiel manager may expect 40% or about 4 of the 10 deployed radio sets to be available for operation at any given time. Approximately 96% of the time the 10 radio sets will not be in active repair.

READINESS CHARACTERISTICS--NORS/NORM

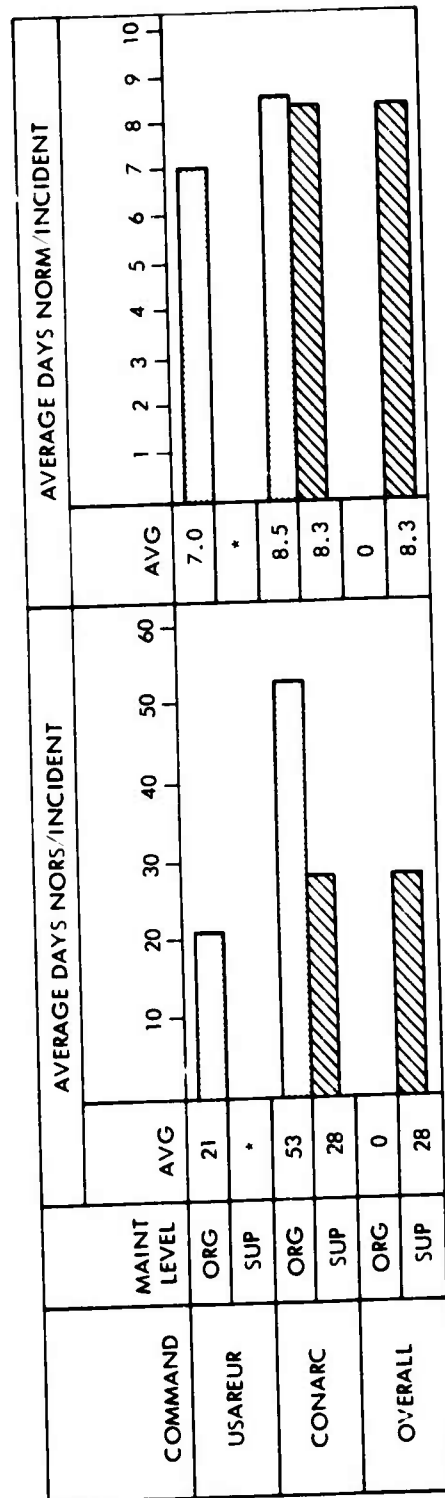


Figure 111-5f portrays, by command, the average number of nonoperational readiness days to supply (NORS), not having the part needed for maintenance, and the average number of nonoperational readiness days due to maintenance (NORM).

When one of the battalion's radio sets becomes nonoperationally ready due to a need for support maintenance (NORM), the logistic planner may expect the set to be in a NORM condition for 8.3 days. When a set is sent to support maintenance for repair and the support maintenance activity does not have the required part needed to effect the repair, the radio set can be expected to be in a NORS condition for 28 days. The materiel manager can therefore anticipate a nonoperational ready period to be extended by 28 days, should the maintenance activity not have the required part needed to effect the repair action.

*No support forms received from USAREUR.

B. REQUIREMENTS, DECISIONS TO ACQUIRE, AND INTERACTIONS WITH SYSTEMS ACQUISITION

*In this world there are only two tragedies.
One is not getting what one wants, and the
other is getting it.*

--Oscar Wilde

The impact of the requirements process is felt throughout the acquisition cycle. Section III-A-1-b (Table III-4) showed that 45 percent of the cost growth of a group of major systems in FY 1972 was due to changes in requirements. The requirements process and its impact are both enormously complex, and a detailed analysis of the intricacies of the different approaches of the Services has been avoided. This examination concentrated, instead, on the following questions:

- Are the formal requirements processes of the Services designed to work effectively?
- If they are subject to aberrations in practice that can drive costs significantly, what are those aberrations?
- What actions can be taken, from the overall points of view of the Services and OSD management, to establish better control over costs through the requirements process?

Although much of the analysis in this section applies quite generally, it has been focused on electronic equipment and systems to the extent feasible and useful.

All the Services use several documents to discuss or establish requirements at various levels of detail and at various points in the decision process. There are wide variations among the Services in both the terminology and the content of these documents. If a "requirement" is defined broadly as an expression of need for a military capability, then a requirement for a specific equipment or system in the most general sense includes a statement of:

1. Physical characteristics
2. Performance needed and desired (including reliability, availability, and maintainability)
3. Numbers of equipments or systems to enter the military forces
4. Costs of planned RDT&E, unit production, and total program
5. Acquisition schedule.

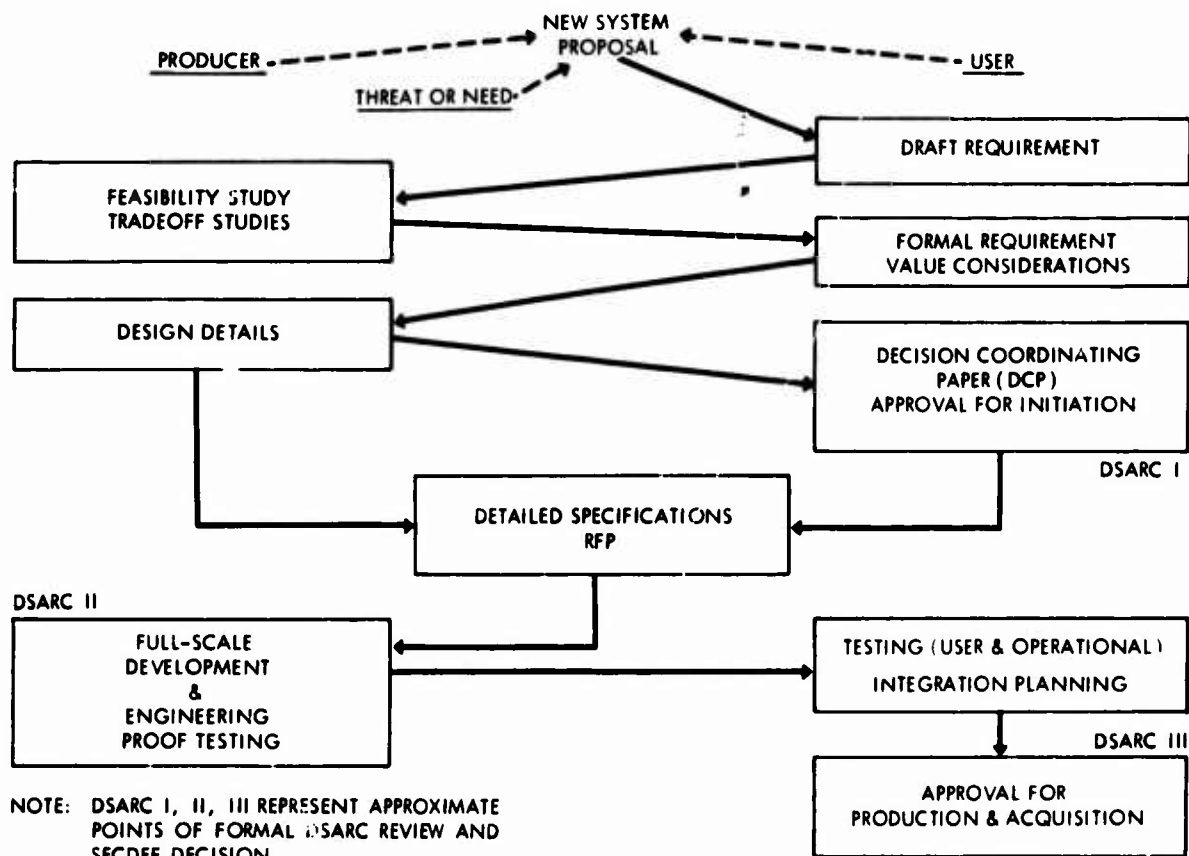
Hereafter, these will be called the five "components of a requirement."

1. The Formal "Requirements Process"

The requirements processes of the Services are currently in a state of change, as the Services recognize their inherent problems and attempt to solve them.¹² At the OSD level, general requirements for military capability are expressed in JCS planning documents, while acquisitions of specific "major" systems (in the sense of DOD Directive 5000.1) are reviewed by the Defense Systems Acquisition Review Council (DSARC) for recommendation to the Secretary of Defense.¹³ Systems less than "major" are reviewed in the offices of the DSARC principals. Parallel organizations exist in the Services, in addition to user requirements review offices and materiel or systems commands. A functional outline of the requirements process, without the Service-peculiar details and complexities, is shown in Fig. III-6. Points where DSARC review is currently required are shown. As a result of the report of the DSARC Cost Reduction Working Group (the "Little Four"),¹⁴ explorations are currently under way to advance the first DSARC review to an earlier time, so that the DSARC would consider approval of a system requirement before the initiation of development.¹⁵ The document used as a basis for major system decisions is the Decision Coordinating Paper (DCP*),¹⁶ in which attention is given to all five components of a requirement.

Experience shows that, to be as effective as possible, the requirements process should (ideally) incorporate a number of operational

*DCP originally stood for Development Concept Paper.



1-17-73-41

FIGURE III-6. Functional Representation of Requirements Process

properties. There must be interaction between the user (the part of the Service that will operate the system) and the producer (the part of the Service, with its laboratories and industrial contractors, that will develop the system and procure it) to ensure that each understands both the technical problems and the operating problems of acquiring and using the system. Before a requirement is established, there must be extensive analyses to gain an understanding of the potential tradeoffs among the five components of the requirement in relation to the threat or need. Uncertainty in assessing the threat and in predicting performance, development cost, and schedule must be recognized and allowed for. As the knowledge of cost, performance, schedule, and threat is refined, the user-producer interaction and the tradeoff analyses must be iterated to ensure that potential or actual departures from the stated requirement (in all five components) are anticipated, recognized, understood, and dealt with.

Most but not all of these properties are inherent in the formal requirements and acquisition decision process illustrated in Fig. III-6. Extensive pre-requirements studies are usually carried out (they always are, for "major" systems), and these involve both user and producer. While uncertainty is often included in such studies, the ultimate expression of a requirement (e.g., in the DCP) does not usually indicate uncertainty ranges and their implications. Nor are tradeoffs among all the components of a requirement necessarily given equal weight at every stage of development of the requirement. Table III-17 summarizes the various formal requirements documents of the Services in terms of the attention given to the components of a requirement in successively more definitive requirements statements. The initial statement, which essentially defines the military capability required, gives no desiderata, or only very coarse ones, as to force size, schedule, and cost. These components are added, essentially as modifiers of performance and physical characteristics, as the requirement becomes more specific. It can be argued, however,

TABLE III-17. STATEMENT OF THE "COMPONENTS OF A REQUIREMENT" IN REQUIREMENTS DOCUMENTATION OF THE SERVICES

<u>Document</u>	<u>Performance</u>	<u>Physical characteristics</u>	<u>Number required</u>	<u>Cost</u>	<u>Schedule</u>
<u>Present Navy*</u>					
General Operational Requirement (GOR)	Broadly stated for 10-20 yr in future	Boundaries & constraints stated	Not stated	Not stated	Not stated
Tentative Specific Operational Requirement (TSOR)	Stated as "desired"	Stated as "tentative"	Stated	Stated as "planned"	Stated as "planned"
Advanced Development Objective (ADO)	Objective stated	Generally stated	Specified, but not stated	Stated	Stated
Specific Operational Requirement (SOR)	Specifically stated	Specifically stated	Stated	Stated	Stated
<u>Proposed Navy</u>					
Research & Development Operational Needs	Broadly stated in 3 periods: far-, mid-, and near-term	Generally stated	Not stated	Not stated (existing annual trade-offs)	Not stated
Advanced System Concept (ASC)	Far-term, broadly stated	Generally stated	Estimate given	Estimate given	Not stated
Advanced Development Proposal (ADP) (DSARC Information)	Mid-term, more specifically stated	More specifically stated	Stated	Good guess	Approximate
Engineering Development Proposal (EDP) (DSARC II and DCP Information)	Near-term, specifically stated	Specifically stated	Stated	Specifically stated	Specifically stated
<u>Army</u>					
Required Operational Capability (ROC) (AF 71-1)	Stated	Stated	Not stated	Stated, preliminary	Not stated
Development Plan (DP) (AF 70-21)	Stated	Stated	Stated	Stated	Stated
<u>Air Force</u>					
Required Operational Capability (ROC)	Stated	Not stated	Estimate given	Not stated	Only IOC given
Program Management Directive (PMD)	Stated (generated by studies & investigations as required by size of task.)	Stated	Stated	Stated	Stated
Program Management Plan (PMP)--Front-Office level	Stated	Stated	Stated	Stated	Stated

* As of May 1971.

that a system offering ideal performance but costing too much to be purchased in the needed numbers, or undeliverable when needed, will provide no more required operational capability than a system that fails to perform as specified. Thus, the formal requirements process would appear to encourage stress on performance before cost, schedule, and force size, leading at the outset to an inherent imbalance in the requirements-acquisition interaction.

2. Some Illustrative Examples of the Impact of Requirements

The initial requirement specification influences cost and related matters throughout the development cycle. The effects can be appreciated best by examining how they have worked in the past, or how they might work on systems currently in development. Nine examples of system acquisitions or requirement specifications have been explored in varying degrees of detail for this purpose. The examples were more or less random, their selection being determined by availability of data, intrinsic interest and variety among the cases, and time available to acquire information about them. The essential relevant information about each example and the main points to be made from its history are summarized in Appendix C. The lessons learned from the examples are discussed immediately below.

3. Aberrations in Implementing the Formal Process

Consideration of the examples cited in Appendix C shows that aberrations in the requirements and acquisition decision process can drive costs through several important phenomena:

1. Misunderstanding the need: demanding performance that is out of keeping with the threat or the job to be done.
2. Insufficient user-producer interaction in establishing the components of a requirement.
3. Insufficient allowance for uncertainty.
4. Insufficient user-producer iteration.
5. Seeking maximum possible performance.
6. Unplanned incorporation of new technology.

7. Inadequate data base for cost and performance estimates.
8. Cascading of requirements at successively lower management levels.
9. Uncertain production base.
10. "No requirement exists" when one should exist; thus, no action is taken to meet the military need.
11. Imperfections in the contracting process.

The full import of these abbreviated statements will become apparent in the succeeding discussion. Table III-18 summarizes the distribution of "lessons learned" across eight of the examples described in Appendix C. It is immediately apparent that none of the cost-driving problems is unique to any program, and that all interact in a complex way. They can be grouped for discussion into three main areas of concern: establishment of the basic requirement; interactions between system management and the characteristics or demands of new technology; and other management problems in implementation.

a. Establishing the Basic Requirement. Establishing a requirement for a system implies a commitment to incur the cost of achieving the specified new force structure, with its intended performance, over the specified implementation schedule. The explicit cost of developing, acquiring, and operating the system can be avoided completely by a decision not to establish the requirement. The consequence is the implicit cost of incurred military and strategic risk in retaining older, less capable systems (or not developing a wholly new capability, such as ICBMs or supersonic fighters with guided air-to-air missiles). Large elements of value judgment, some components of which can be quantified, are involved in making the choice.

While this formulation greatly oversimplifies the nature of the tradeoffs, there remains immense flexibility for choice between the extremes, implying more or less expenditure. Initially, it might be argued that a new system will allow a task to be performed less expensively. History has shown, however, that the more advanced systems generally cost more.¹⁷ The argument is then reduced to

TABLE III-18. EXAMPLES OF SYSTEM ACQUISITIONS OR REQUIREMENT SPECIFICATIONS AND THEIR INTERACTION WITH ABERRATIONS IN THE REQUIREMENTS PROCESS

Aberration Example	1	2	3	4	5	6	7	8	9	10	11
	Misunder- standing the Need	Insufficient User- Producer Interaction	Insufficient Allowance for Uncertainty	Insufficient User- Producer Iteration	Seeking Maximum Possible Performance	Unplanned Incorporation of New Technology	Inadequate Data Base for Estimates	Compound- ing of Require- ments	Uncertain Production Base	Require- ment Unstated	Imperfec- tions in Contracting Process
Mark II Avionics for F-111	•		•	•	•		•	•			
C-SA Navi- gation Subsystem	•	•	•	•	•	•	•	•			•
Air-to- Air Missiles			•		•				•		
Armed Hell- Copter	•		•	•	•	•	•	•			
Main Battle Tank	•	•	•	•	•	•		•			
LOWAN C/D		•			•		•			•	
PAVE OPTIC Laser- Guided Bomb									•	•	
COMBAT EAGLE		•				•				•	

comparative cost-effectiveness; the case for the new system can sometimes be demonstrated conclusively but is more often subject to argument, especially about the assumptions entering the analysis and about the value or validity of performance measures.¹⁸ Much of this argument revolves around uncertainties in the projected performance in relation to the projected threat or need. Within the bounds of such uncertainties, it may be possible to achieve the desired performance, at less cost, although at increased risk, by using technological advances to improve one or a few elements or components of an existing system rather than to develop a wholly new system.

Figure III-7 shows the progression of costs through successive new generations of a variety of military systems that depend heavily on electronics for their effectiveness. With the cost increases, of course, went performance increases; while these are difficult to measure in commensurate terms for the disparate systems, Table III-19 suggests the nature of the improvements for some of the systems in a qualitative way. Figure III-8 shows the cost growth of electronic subsystems for the systems represented in Fig. III-7. Figure III-9 shows similar data for more modest within-generation system improvement, and Fig. III-10 shows the corresponding data for the electronic subsystems involved. Table III-20 shows the qualitative changes in performance achieved for these within-generation system modifications.¹⁹

Although the data in Figs. III-7 through III-10 are approximate, the trends they imply are instructive. For the complete systems shown, the new-generation system costs increased, on the average, by about a factor of 5 per decade (Fig. III-7), while the "product improvements" increased, on the average, by only a factor of 2 (Fig. III-9). The electronic subsystems of these systems increased much more rapidly: an average factor of 10 per decade for the electronics of the new-generation systems (Fig. III-8), and 6 per decade for the electronics of the "product improvements" (Fig. III-10). As Table III-21 shows, the cost of new-system electronics tended to increase faster than that of "product-improvement" electronics.

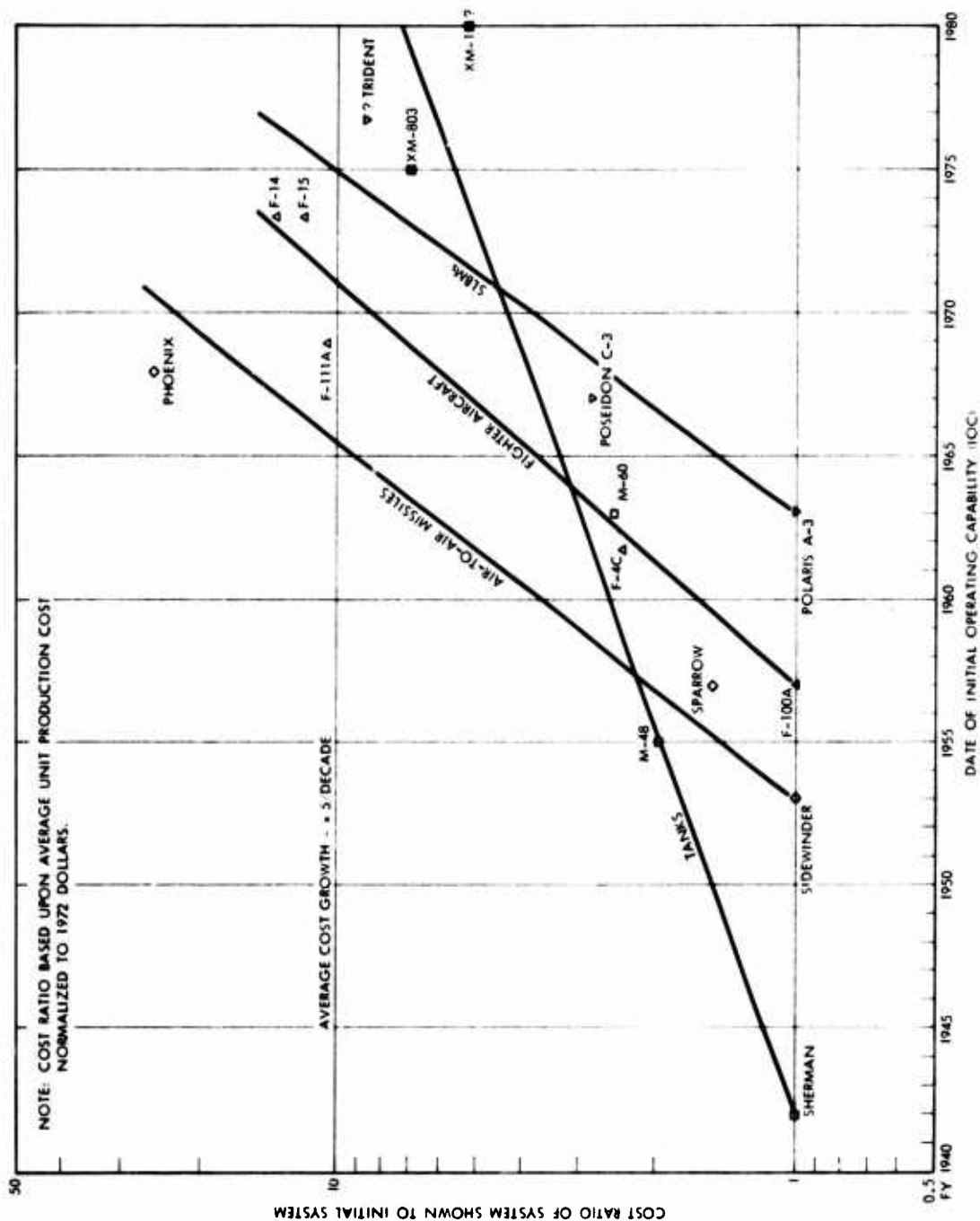


FIGURE III-7. New-Generation Cost Progression for Systems Shown ¹⁹

TABLE III-19. PERFORMANCE IMPROVEMENTS IN
NEW-GENERATION SYSTEMS

Fighter Aircraft

- Aerodynamic Performance
- Size, Type, and Diversity of Load
- Range and Accuracy of Target Acquisition and
Weapon Delivery
- Night and Weather Operation

Air-to-Air Missiles

- Range
- Size of Engagement Envelope
- Accuracy
- Lethality

SLBMs

- Range
- Accuracy
- Payload

Tanks

- Firepower
- Extended Combat Conditions (Night, Moving)
- Agility
- Armor
- Range and Speed

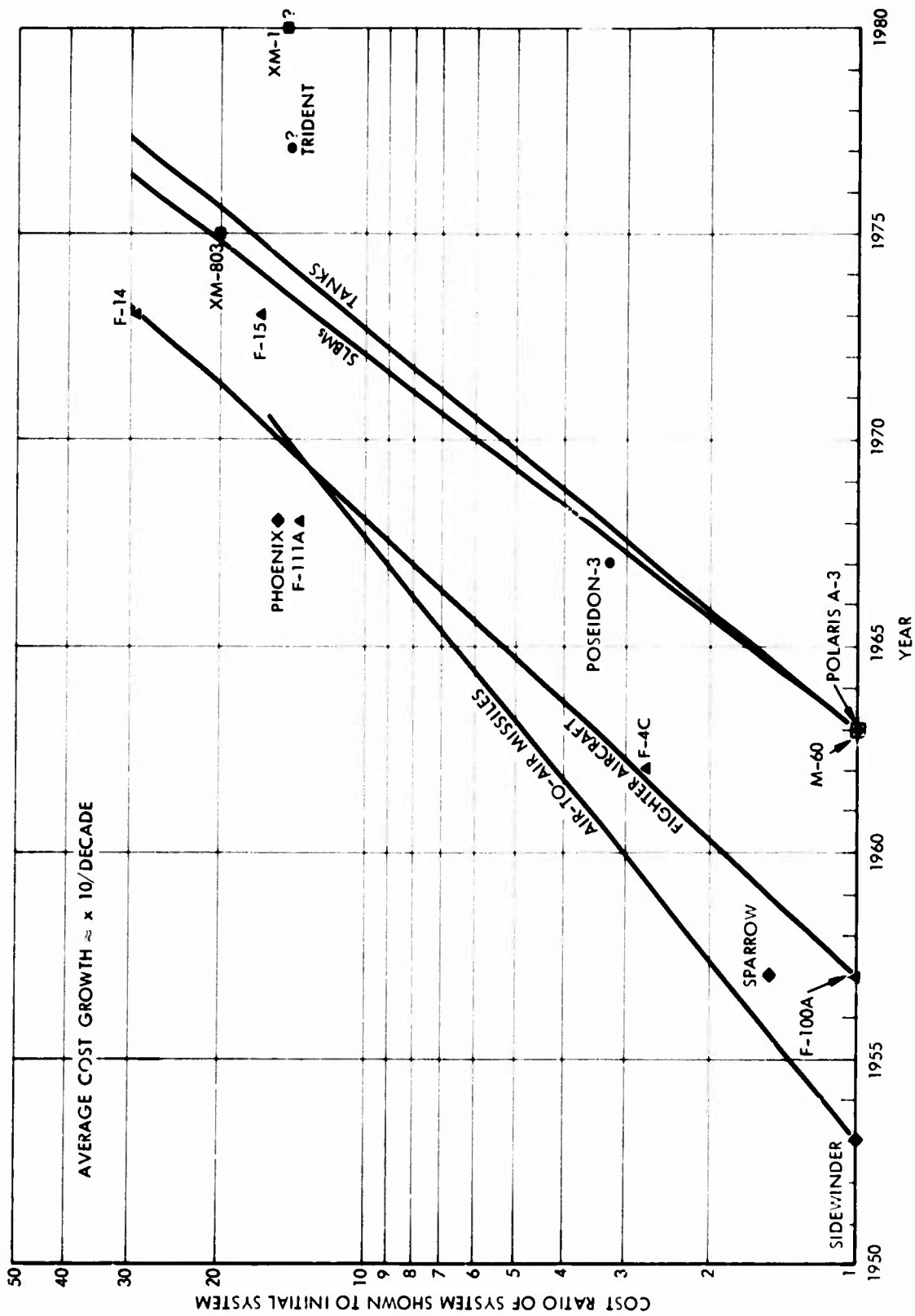


FIGURE III-8. New-Generation Electronic Subsystem Cost Progression for Systems Shown ¹⁹

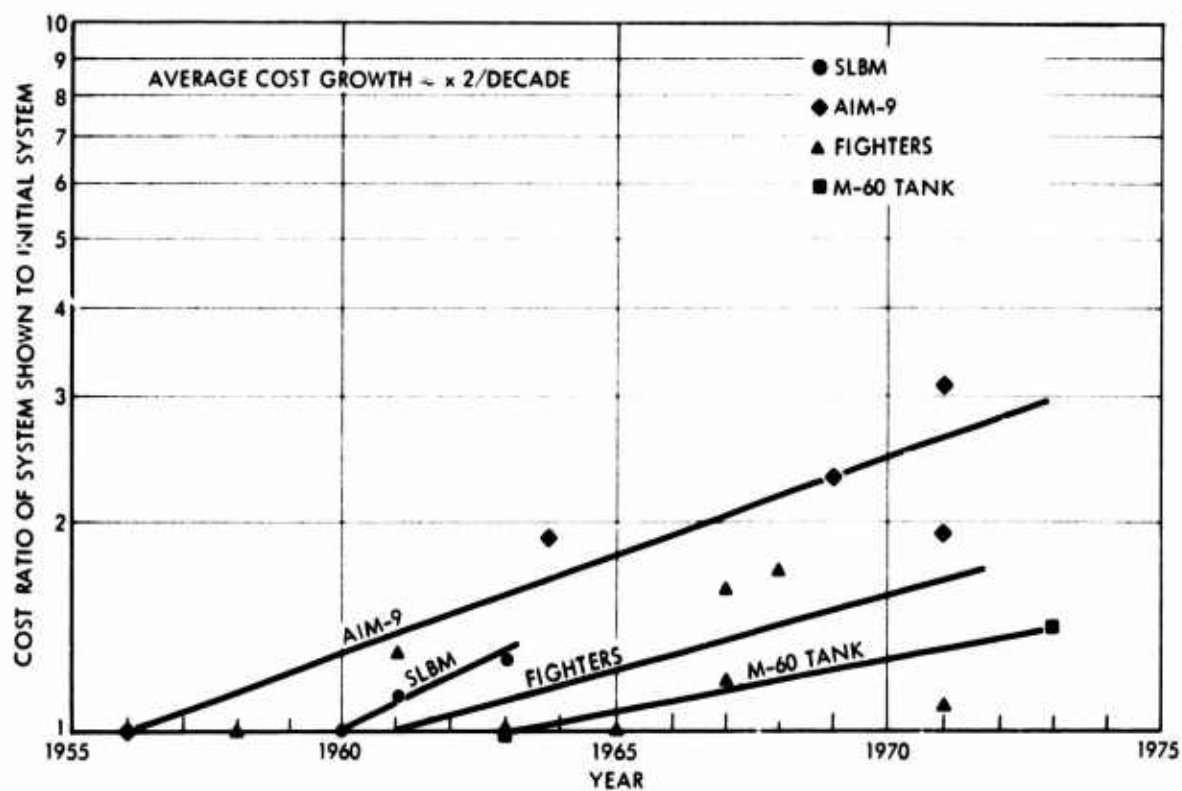


FIGURE III-9. Within-Generation Cost Progression for Systems Shown, Total System ¹⁹

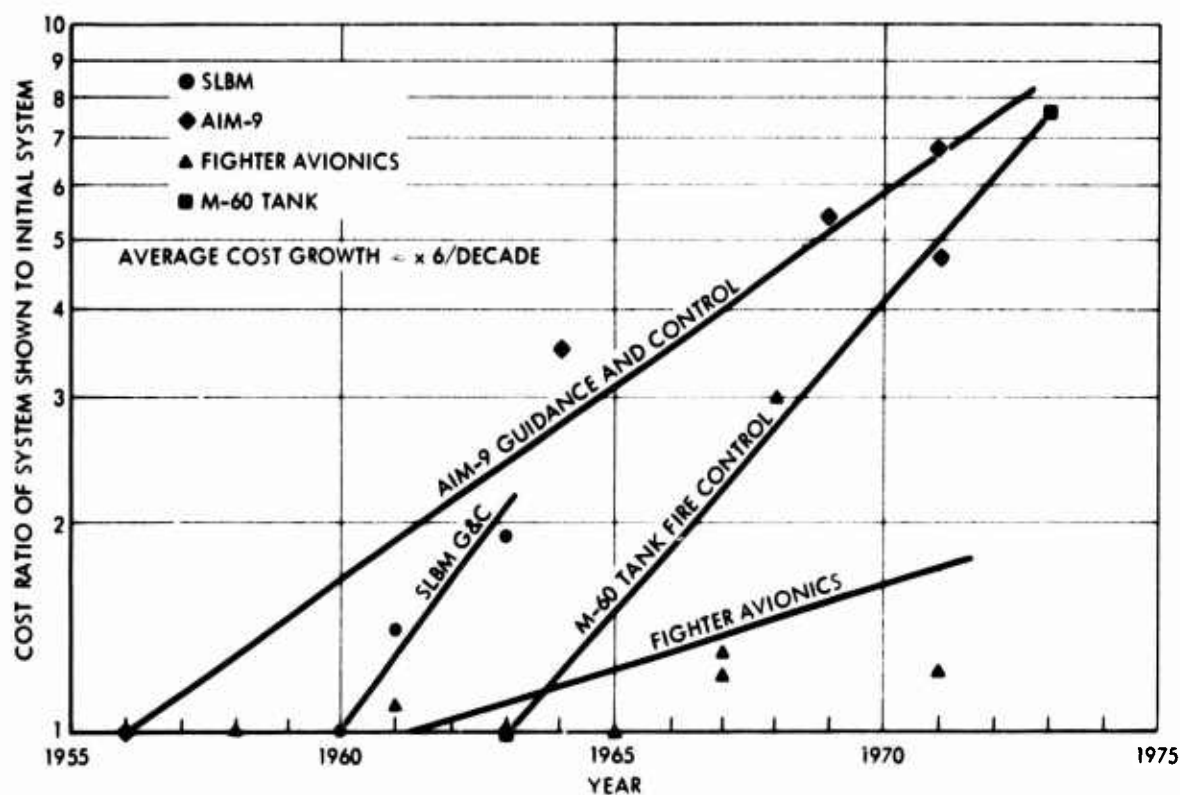


FIGURE III-10. Within-Generation Electronic Subsystem Cost Progression
for Systems Shown ¹⁹

TABLE III-20. PERFORMANCE IMPROVEMENTS WITHIN GENERATIONS

Fighter Aircraft

- Range of Conditions (Night, Weather) under which Targets can be Acquired
- Diversity of Air-to-Air and Air-to-Ground Modes
- Accuracy of Navigation and Weapon Delivery
- Electronic Countermeasures
- Aerodynamic Performance (Some)

AIM-9 Air-to-Air Missile

- Acquisition Capability
- Size of Engagement Envelope

POLARIS A-1--A-3 SLBM

- Range
- Accuracy
- Penetration Capability

M-60 Tank

- Armament
- Accuracy
- Shoot-while-Move

TABLE III-21. AVERAGE PER-DECADE COST-GROWTH FACTORS
FOR SPECIFIC TYPES OF SYSTEMS
(Based on 1972 Dollars)

<u>Type of System</u>	<u>Total- System Factor</u>	<u>Electronic- Subsystem Factor</u>	<u>Approximate Electronics Percentage of Total System Cost</u>
<u>New Generation:</u>			
SLBM	7	14	15% (1960)--25% (1980)
Fighter Aircraft	5 ^a	9	10-20% (1958)--20-30% (1973)
Air-to-Air Missile	6	6	60-90% ^b
Tank	2	12	6% (1963)--45% (1975)

"Product Improvement":

SLBM ^c	2	11
Fighter Aircraft ^d	2	2
AIM-9 ^e	2	4
M-60 Tank ^f	1	8

^aA factor of 3-4 is shown in Fig. II-4, p. 58; this difference comes about because the baselines are different. The data here reflect roughly the decade of the 1960s (1958-1973), whereas the data in Fig. II-4 cover 1918-1973.

^bDepends on missile and range.

^cPOLARIS A-1--A-3 (extrapolated).

^dF-4B-J; A-4C-F; A-7A-E; A-6A-E.

^eAIM-9B-J.

^fM-60A1 and M-60A3 (excluding M-60A2).

It can be inferred from these data that much of the cost increase in "product improvements" is due to changes in the electronic subsystems. With the rapid pace of technological change in electronics, the large rate of electronics cost growth suggests that several generations of change in electronic technology were involved in each sequence of within-generation system improvement.

The data of Figs. III-7 through III-10 and Tables III-19 and III-20 suggest two avenues to potential cost savings through the establishment of requirements. By the first avenue, overall system costs could be reduced through increased reliance on improvement of existing systems, consistent with views of threat or need (the latter are, of course, subject to various interpretations). This is probably true for electronic subsystems as well. The costs of integration and meeting IOC for a wholly new electronic subsystem development undertaken as part of a wholly new aircraft system, for example, is likely to be higher than the cost of improving a subsystem of an existing aircraft. Other systems might follow this pattern. For a new-generation system, as compared with an improved system, it is probably also true that subsystem performance requirements are heightened to capitalize on the greater capabilities of the platform, and this points to the second avenue to cost savings.

The majority of military electronics--roughly 80 percent of the dollar value*--is carried on ground, sea, air, or space vehicles as parts of integrated systems. The vehicle ordinarily carries weapons or equipment to a location to do a job. (Sometimes, as in a communication or navigation satellite system, the sole purpose of the vehicle is to carry the electronics.) Usually, the amounts of time required and the technical problems to be solved in developing a vehicle (be it tank, ship, aircraft, or missile) and its electronic subsystems differ considerably. While development of independent

*See pp. 50 and 51, particularly Table II-1.

electronic subsystems need not be tied to the same schedule as development of their vehicles,* very often primary electronic subsystems and their vehicles are tied to the same development schedules [e.g., the main battle tank (MBT) fire control system, the HELLFIRE laser guidance, the F-111B PHOENIX, and the C-5A navigation system].

Although the time available for this study did not permit quantitative exploration of many examples of alternative approaches, a few examples such as the E-2C and the B-1,²⁰ as well as the data of Figs. III-7 through III-10, suggest that separating vehicle development from electronic subsystem development may result in considerable savings. For most systems in development, there is likely always to be a useful subsystem to fit to the vehicle while a more advanced subsystem is developed for it.* That is, improvement of total system capability can be taken in two steps. Of course, if scheduling of electronic subsystem development independently of vehicle development is to succeed, increased attention to form-fit-function standardization, discussed in Section IV-B, is essential. It follows, also, that in this mode similar subsystem or equipment requirements for a number of systems might be merged, making additional savings possible.

One practical implication of the choices outlined above is that if, in a period of budget constraint, a commitment is made too early to a completely new-generation system, resources will be unavailable for other necessary systems. Conversely, if the threat or need changes earlier than anticipated after the within-generation electronic system change has been chosen, or if the development schedules for the vehicle and the electronic subsystem have been separated, necessary performance may become available too late.

* For example, the XM-803 tank could have been fitted initially with the M-60 tank armament and fire control system, upgraded afterwards to that planned for the M-60A2 or M-60A3 tank, and later to that currently visualized for the XM-1. Similarly, a laser guidance system could be developed independently and then retrofitted to TOW, a new airframe-motor design following at another time. The C-5A could have been equipped initially with C-141 avionics, thereby not internalizing to the C-5 development the cost growths illustrated in Fig. C-2, Appendix C.

The preceding discussion is not meant to imply that the conservative choices are never taken; they are. It is, here, a matter of emphasis. The uncertain and often arbitrary considerations involved are illustrated by several examples treated in Appendix C [the Mark II avionics, the C-5 navigation system, the Advanced Attack Helicopter (AAH), and the MBT]. While the decision rules cannot be prescribed a priori for all future system selections, the large variations in cost-per-change slope that are inherent in the data presented suggest that this decision area, which appears at the beginning of the acquisition process, offers very great leverage on systems acquisition costs.

Associated problems in the requirements-decision process emerge from the examples discussed in Appendix C. Although many important systems (e.g., SIDEWINDER, SSB-HF, ICBM, Gunship) have been built in the absence of a formal requirement statement because a need was apparent, the cases of LORAN-D, PAVE SPIKE, and COMPASS EAGLE show that failure to establish a requirement can exact a price. Delay in establishing a requirement and small differences between Services regarding characteristics can reduce the production base or make it uncertain, raising total procurement costs. Often, subsystems are accepted implicitly as part of a total system requirement that is approved without full appreciation of the cost-driving implications for the subsystems (as exemplified in Table C-3, Appendix C).

b. Interactions between Management and Technology. Figure III-11 illustrates schematically a typical set of events in the development of a system or subsystem using new technology. While the illustration is intuitively satisfying, it is difficult to assemble extensive data to establish Fig. III-11 as factual. One such real case is illustrated partially in Fig. III-12.²¹ For comparison with actual cost experience, data could not be found regarding the initially proposed costs for the systems included in the two regression curves. However, the figure does illustrate the tendency to move in both the increased cost and performance directions when moving to a new technology.

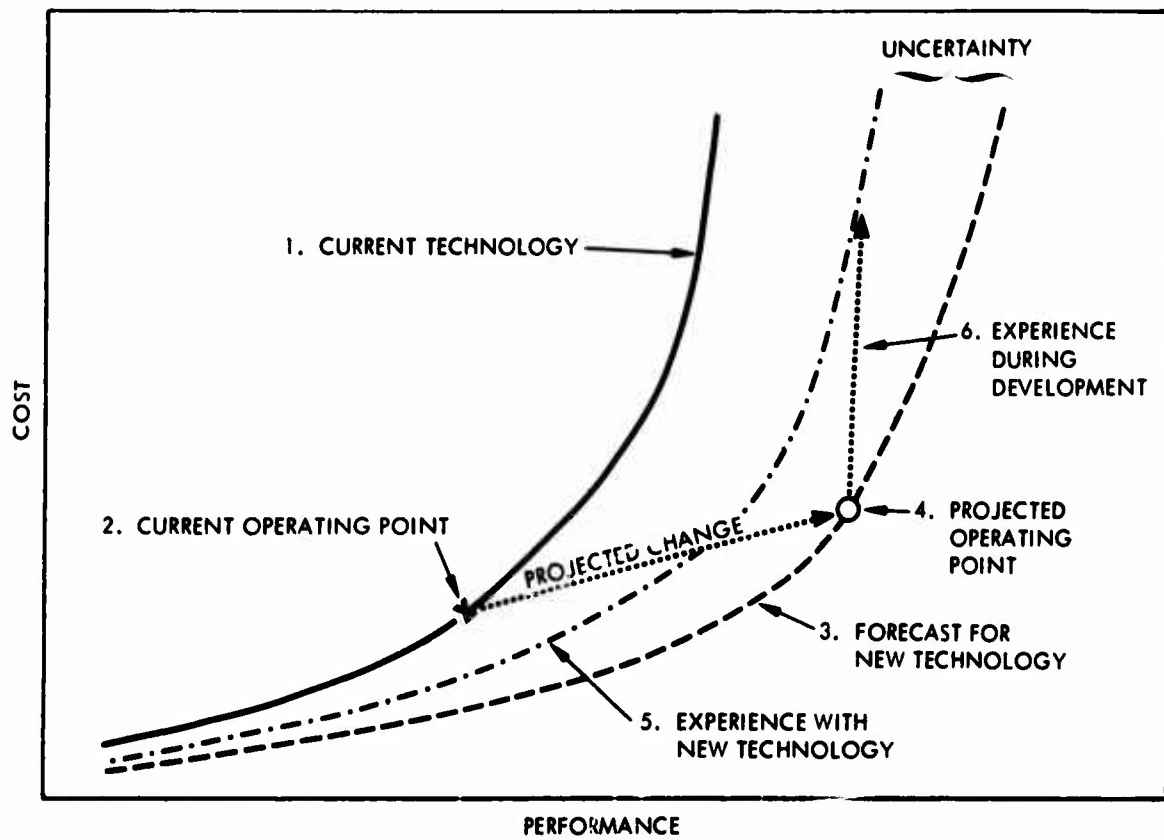


FIGURE III-11. Impact of Uncertainty on Systems Acquisition Costs and Performance

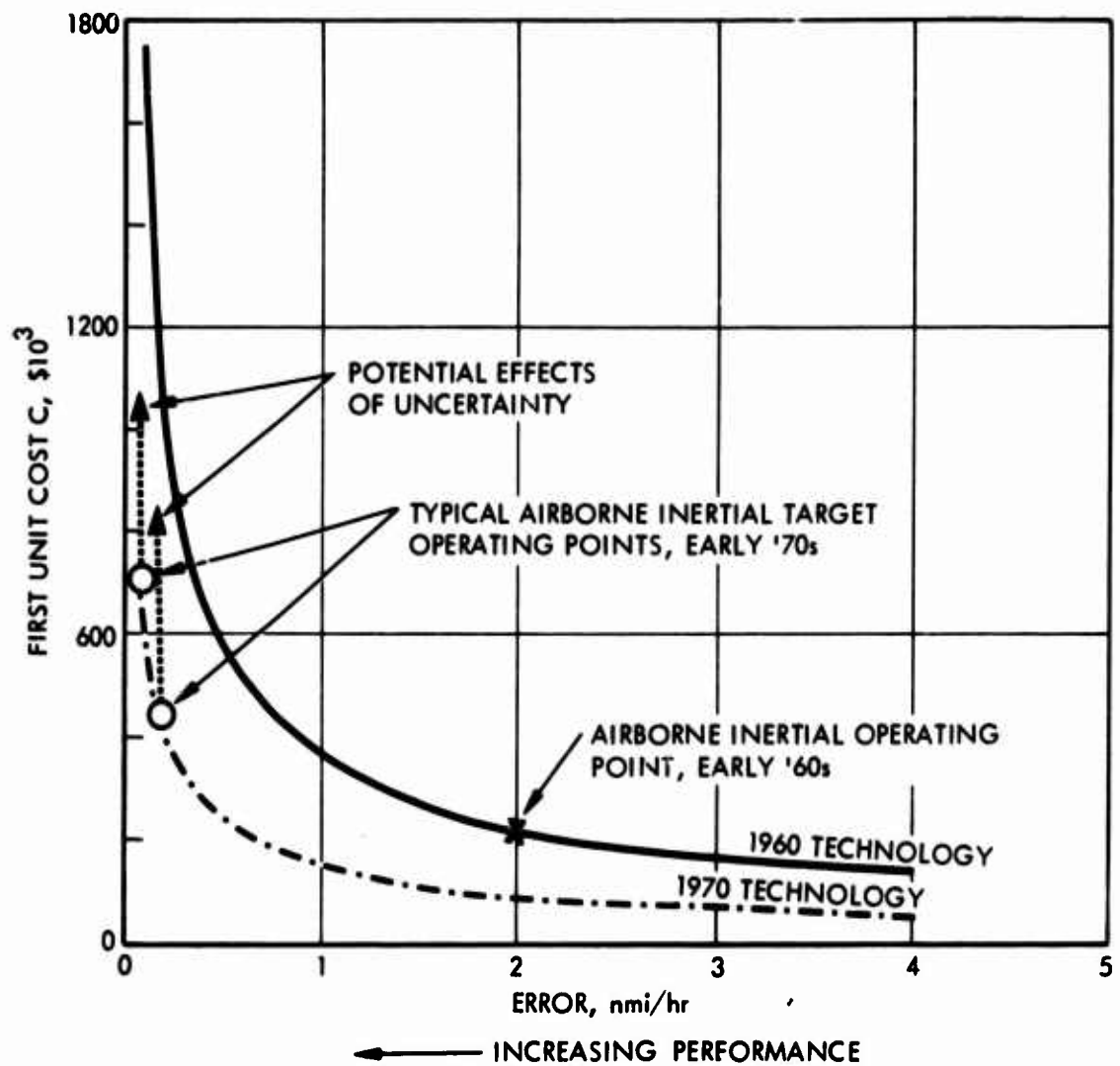


FIGURE III-12. Cost-Performance Curves for Inertial Navigation Systems²¹

Figures III-11 and III-12 illustrate not only the effect of technological uncertainty, but also the danger of selecting a proposed operating point too far up on the cost-performance curve. As a general matter, advancing the technology to a new curve for any system, as shown in Fig. III-12, would incur the "buy-in" costs as part of that development, as happened in the floating-ball-gyro inertial navigation system (INS) for the C-5A. This gives additional cause for conservatism in establishing requirements; but conversely, it can make technological advance more difficult to achieve.

The user-producer interaction in establishing the requirement amounts, essentially, to estimating the curve for the new technology and deciding where on that curve the new operating point should be. As illustrated by the case of the Mark II avionics, if there is wide divergence of opinion on these matters the result can be costly. The producer may claim more for the technology than he can deliver, or he may underestimate the cost of delivering what can ultimately be achieved. Alternatively, the user may not know enough about the new technology and may therefore demand what ultimately cannot be delivered. Since the user is usually in a commanding position in a Service, he can strongly influence both the producer within that Service and the producer's in-house or industrial contractors to acquiesce in such demands in order to be responsive and--in the case of industry--to capture the business despite the risks.

Another source of cost-driving uncertainty is the "requirements pyramid" illustrated in Table III-22. For the AAH, there are: eight performance requirements stated in the DCP; 250 in the "Materiel Need" (MN), which is the main document (together with the development plan) that will guide the program manager; approximately 400 in the RFP (e.g., in the RFP there are three specifications associated with the IR detector of the copilot-gunner's FLIR, while the detector is subsumed as part of the specified FLIR in the MN); and an as yet unknown but larger number of specifications that will appear at the detailed implementation level. In approving a program for a major

TABLE III-22. TYPICAL REQUIREMENTS PYRAMID

<u>Level</u>	<u>Number of Requirements/ Specifications Explicitly Expressed</u>
Top System Decision Level	Order of 10
Requirement Statement	Order of 10^2
RFP	Order of $K \times 10^2$
Detailed Implementation	Order of 10^3

TABLE III-23. QUESTIONS TO BE ANSWERED ABOUT ELECTRONIC SYSTEMS AND SUBSYSTEMS DURING MANAGEMENT REVIEW

- What components exist?
- What components need new development?
- What is the development/test status of existing components?
- Are new technologies involved? If so, which, and what is their status?
- Have the components previously been integrated into a subsystem?
- If so, has it been operated outside the laboratory?
- Has there been subsystem OT&E?
- How do results compare with requirement?
- What are the specific interface problems with other subsystems?
- What are the cost, performance, and schedule implications of resolving those problems in this new development?
- What are the options if there is excess cost growth?
 - a) Alternative components/subsystems?
 - b) Let cost grow?
 - c) Reduce performance requirement?
 - d) Reduce force?
 - e) Find another way to do the job?

system, the DSARC and comparable Service bodies may not be aware of lower-level requirements statements,* which can later make the cost "designed to" difficult to hold.

The cases of the AH-56 fire control system and potential problems in fitting capability of the PAVE SPIKE type to the A-7 and the A-10 illustrate the potential effects on cost of failure to plan well in advance for incorporation of new technology in an existing system or a new system. This need is consistent with the idea of evolutionary development. The point is not that new technology should not be adopted as it becomes available, but rather that it should be adopted in an orderly manner after careful development with a system application in view.

Table III-23 lists a series of questions about electronic subsystems that can assist, during management review (at Service or OSD level, and in connection with broad reviews based on the DCP), in eliciting a priori the sources of potential cost growth without requiring high-level management to learn all the details of proposed system requirements and plans (although a review in detail by supporting staff would obviously be necessary). The questions synthesize and reflect the requirement and uncertainty problems of major subsystems that emerged from the examples examined in Appendix C. As shown in Table III-24, the answers to these questions can indicate in straightforward fashion the degree of risk involved in undertaking a development. This understanding can then help in establishing where in the uncertainty range the cost designed to and the performance figures should be set; it can help in assessing the risks attending approval of development; and it can help in making the judgment of potential worth of the development in light of the risks of cost growth potentially incurred.

*For example, failure in the MN to specify weather and detection probability for a day-night sight (as happened in the AAH program) may result in overdesign of a system to meet the worst conditions. Note also the original performance specification for the navigation system of the C-5A.

TABLE III-24. HIGHLY SIMPLIFIED EXAMPLES OF RISK ASSOCIATED WITH SOME POSSIBLE ANSWERS TO QUESTIONS IN TABLE III-23

<u>Questions</u>	<u>Answers</u>		
	<u>High-Risk</u>	<u>Medium-Risk</u>	<u>Low-Risk</u>
• What components exist?	None	Few (named)	All
• What components need new development?	All	Few (named)	None
• What is the development/test status of existing components?	Laboratory	Developed, not produced	Developed, not produced
• Are new technologies involved? If so, which, and what is their status?	Yes	No	No
• Have the components previously been integrated into a subsystem?	No	Partially	Yes
• If so, has it been operated outside the laboratory?	No	Field test	Field test
• Has there been subsystem OT&E?	No	Partial	Yes
• How do results compare with requirement?	--	Partially ^a	Well ^a
• What are the specific interface problems with other subsystems?	All (named)	All (named)	Few (named)
• What are the cost, performance, and schedule implications of resolving those problems in this new development?	Moderate to high ^a	Moderate ^a	Low ^a
• What are the options if there is excess cost growth?			
a) Alternative components/subsystems?	None	Yes	Yes
b) Let cost grow?	Yes	Yes	--
c) Reduce performance requirement?	Yes	Yes	--
d) Reduce force?	Yes	Yes	Yes
e) Find another way to do the job?	None	None	Several exist

^aBased on numbers given.

c. Other Management Problems in Implementation. Section III-A, on cost uncertainty, has shown that costs are likely to be underestimated at the inception of development. Important causes have been illustrated in Figs. III-11 and III-12 and in Table III-22 and have been discussed. As indicated in Section III-B-2, the decision to establish a requirement involves a value judgment, usually supported by analysis, that anticipated costs are worth incurring to meet an anticipated threat or need. This judgment might be made differently if the true cost were appreciated at the outset. Alternatively, if cost growth were sensed early after a development began and adjustments were made in expected performance, as shown by the alternate development path in Fig. III-13, cost growth might be smaller but so would the performance achieved. This, too, might lead to a different judgment of need if anticipated at the time of the requirement decision.

This suggests an iterative decision process, as experience is gained in development and leads to a continually improving view of the performance, schedule, force size, and cost that will actually be achieved. Although sunk cost and time lost must be allowed for in deciding whether to proceed further at any point, it is clear that the value of the "required" system is always implicitly (if not explicitly) in question as its requirement parameters change. In many cases, there will be (or could be) an existing system (with potential improvements) to fall back on, thereby continuing the competition between development alternatives from the initial requirement decision through development. This continuing review can take place within the developing Service, between the Service and OSD, or both.

It is apparent that if the DOD is to retain the flexibility to change systems as a result of this iteration of requirements review, the development contract structure must permit such changes, balancing equity for the contractor in recovering costs against the Government's need to change direction without excessive penalty. The examples of the Mark II avionics and the C-5A navigation subsystem illustrate that the Government can become locked into a contract that makes change

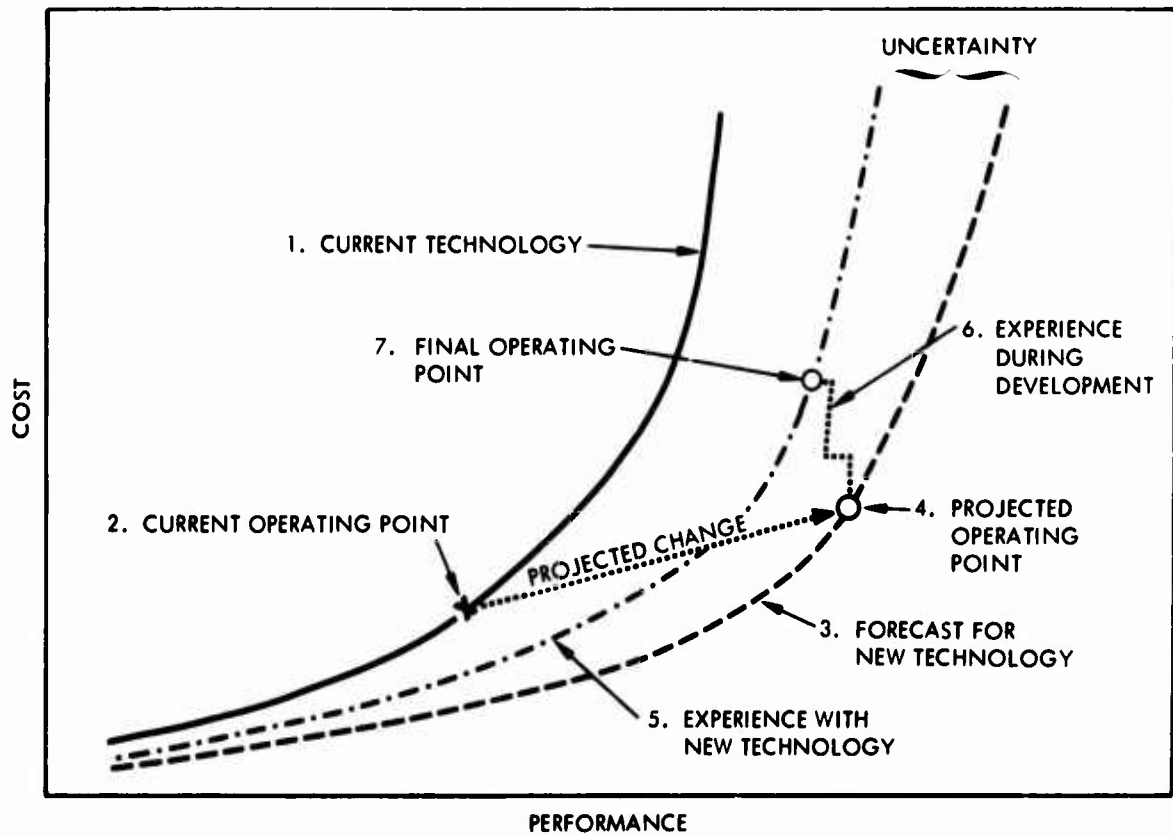


FIGURE III-13. Potential Effect of Iterating Requirements Review

expensive, even when one can predict with reasonable certainty that there will be undesirable cost growth under the contract as written.

4. Classification of Electronic Systems for Management

There are clearly differences in the electronic content, purposes, and management problems of various system and subsystem acquisitions. These differences require differing treatment in acquisition management. Further, systems and subsystems can be aggregated into a small number of groupings such that the systems in each may be treated similarly.

A natural division occurs between systems that are large enough to qualify for review by DSARC criteria* and systems that are not. Within the former group, some (such as command-control, electronic warfare, or large-scale communications systems) are primarily electronic, while others (such as fighter aircraft, tanks, or ships) have major electronic subsystems that are developed as parts of the total systems. Some systems, such as missiles, can fall into either category. Table III-25 lists examples of systems of both kinds and of missile systems as well, and it shows also the estimated percentages of the costs of system development devoted to electronics.²² Inspection of these examples discloses a useful subdivision between systems for which the electronic portion of costs (RDT&E, or total acquisition, or both) is 50 percent or greater, and those for which the electronics cost is less than 50 percent but greater than 10 percent.

Electronic systems and equipment below the DSARC threshold also appear to fall into two major groups. One includes subsystems being independently developed for inclusion in major systems (such as LORAN-D or PAVE SPIKE); the other includes electronic systems and devices designed for specific direct applications, such as Army field radios or night-vision devices. While major systems (by DSARC criteria) are

*A "major" system is defined by any or all of the following: \$50 million RDT&E; \$200 million procurement; and national urgency.

TABLE III-25. ELECTRONICS PERCENTAGES OF RDT&E COSTS
OF SOME MAJOR SYSTEMS

<u>Systems Primarily Electronic</u>	<u>Electronics Cost Percentage^a</u>
Submarine Sonar AN/BQQ-5 (Navy)	100%
SATCOM (Army)	90
TACFIRE (Army)	90
VAST (Navy)	90
SATCOM (Navy)	80
ABNCP (Air Force)	50
AWACS (Air Force)	50
E-2C (Navy)	50
 <u>Systems Having Major Electronic Subsystems</u>	
XM-1 (Army)	25-40%
AAH (Army)	20-30
F-14 (Navy)	20-25
F-15 (Navy)	18-22
F-4 (Air Force)	15-20
B-1 (Air Force)	10-15
UTTAS (Army)	10
 <u>Missile Systems</u>	
AIM-9 (Navy)	40-80% ^b
PHOENIX (Navy)	50 ^c
CONDOR (Navy)	40-50
SAM-D (Army)	40-50
DRAGON (Army)	35
LANCE (Army)	20

^aSource: Ref. 22.

^bDepends on version.

^cPart of PHOENIX cost is in F-14 program.

usually each assigned a single line item in the budgeting process, smaller developments in a related applications area are grouped within a single line item. Table III-26 illustrates such aggregations.²³ The significance for program review is, of course, that developments or procurements of the kind illustrated in Table III-26 must be identified individually rather than by line item.

From the above considerations, the following electronic system classification is suggested for purposes of acquisition management:

- Class I: Major systems by DSARC criteria, 50 percent or more of whose cost is in electronics.
- Class II: Electronic subsystems of major (DSARC) systems, representing 10 percent or more of total system cost, and included within and scheduled with the major system acquisition.
- Class III: Electronic subsystems, multipurpose in character, developed independently for use in many major systems, and themselves below the criteria for major systems.
- Class IV: Other electronic systems and devices, below DSARC criteria, that do not fall into any of the above categories.

Review of the systems in the FYDP shows a distribution of numbers of separate developments falling into the above categories as listed in Table III-27. The assignments to the different classes are, in this case, largely judgmental, for purposes of illustration. If there were interest in this classification system, final assignment would have to be made by DOD according to its own management judgment. Class I and Class II categorization would appear "cut and dried," by the definitions; the major difficulties would be in determining the fraction of system cost devoted to electronics and in defining the electronic subsystems appropriately. The problem of establishing criteria to identify Class III and Class IV systems for particular management attention will be discussed below in the context of management options for improved control of system costs.

TABLE III-26. TYPICAL LINE-ITEM BREAKDOWN FOR INDEPENDENT
SUBSYSTEM DEVELOPMENTS^a

<u>Program Element 6.3206N, Airborne Electronic Warfare Equipment, Includes:</u>	<u>Program Element 6.3202N, Avionics, Includes:</u>
W3311 - Airborne Defensive CM	W3150 - All-Application Digital Computer
W3312 - Airborne Infrared CM	W3342 - Advanced AEW Radar
W3344 - Expendable Jammer	W3415 - Carrier Aircraft Inertial Navigation
W3351 - Integrated Tactical ECM	W45X1 - Advanced Aircraft Electric- al System
W3355 - Visual CM	
W3360 - Tail Warning/ Communications Jamming	
W3361 - Sup. Bandwidth/Dual-Mode DECM	

^aSource: Ref. 23.

TABLE III-27. APPROXIMATE NUMBERS OF PROGRAMS, BY CLASS

<u>Class</u>	<u>Category</u>	<u>Electronic System Classification</u>	<u>Estimated Number of Programs</u>
I	Major Electronic Systems	Electronics ≥ 50% of total system cost	23
II	Major Systems with Important Electronic Subsystems	Electronics < 50% of total system cost	75
III	Independently Developed Electronic Subsystems for Major Systems	Separate Electronic Subsystems	500-1,000
IV	Electronic Equipment and Support	All Other Acquisition	1,000-10,000

A breakdown of the DOD systems acquisition budget for FY 1974 (taken as reasonably typical for the present) is shown in Fig. III-14. While there is considerable uncertainty in the estimates of the electronic content of the various classes of system, some interesting and useful conclusions can be drawn from the figure. Of the \$21.9 billion FY 1974 total acquisition budget, some 85 percent, or \$18.7 billion, is estimated to be devoted to systems having significant electronic content (i.e., electronic subsystems costing 10 percent or more of total system cost). Top-level management attention to Class I and II systems, already institutionalized through the DSARC and its Service counterparts, ensures such attention to about 70 percent of the \$18.7 billion; if intensified attention is given to the electronic components of these systems, which could drive costs and without which the systems could not operate effectively, 35-50 percent of the electronic acquisition budget would be affected. Class III systems, taken as essentially all electronic, are least certain in definition as a class, but involve a large fraction of the electronic acquisition budget--30-50 percent. This amounts to only 12-20 percent of the total acquisition budget, however. Class IV acquisitions, although many in number, represent the smallest fraction of either the total or the electronics acquisition budget.

5. Options for Management Control of Electronics Acquisitions

A few broad types of management action by OSD and the Services might be of assistance in reducing the cost of electronic system acquisition through the requirements and associated review processes. These include:

1. Improving the electronic components of existing-generation systems rather than acquiring wholly new-generation systems, whenever this can be done within the uncertainty bounds of threat or need.
2. Decoupling electronic development schedules from platform development schedules, where the two are separable, and incorporating new electronic systems only when reliability is proven.

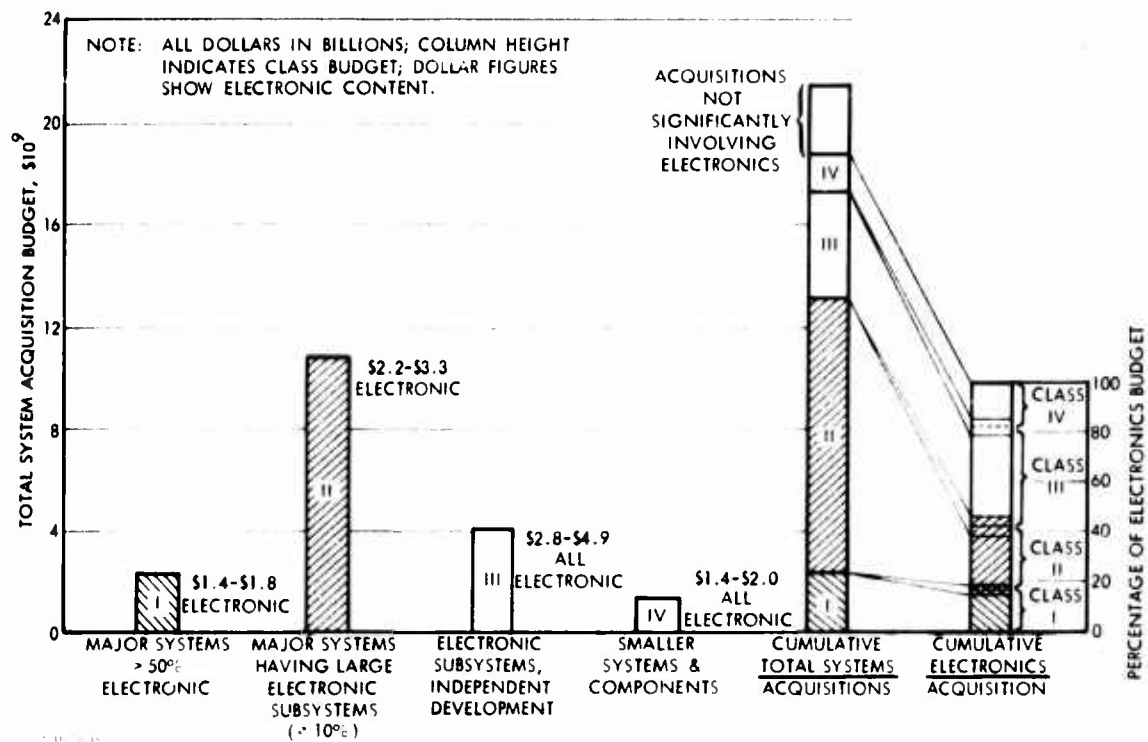


FIGURE III-14. FY 1974 DOD Acquisition Budget (R&D and Procurement), by Class of System

3. Improving the visibility, to top management, of potentially cost-driving electronic subsystems of major systems, before requirements are established.
4. Allowing for technological and cost uncertainties in establishing cost, performance, and schedule requirements.
5. Iterating user-producer interaction and requirement review as experience is gained during development and initial production.

To implement these principles, the four classes of system must be treated differently. Table III-28 shows that the principles do not apply to each class of system in the same way. Further, review and approval of the kind and at the level applied to electronics of Classes I and II cannot be applied to electronics of Classes III and IV, simply because of the much larger numbers of developments and procurements involved. The OSD and the Services can best prescribe the approaches that appear most feasible for implementation. Six possible options, oriented toward a better focus of management attention on specific problem areas by the established review and decision mechanisms rather than by expansion or drastic change of those mechanisms, are as follows:

1. Since the appropriate responsibilities and authorities are already assigned in the OSD and the Services, internal guidance can simply be issued to give increased attention to these points. In particular, answers to the kinds of question listed in Table III-23, regarding the primary electronics of Class I systems, the major subsystems of Class II, and the potential developments of Classes III and IV, would assist in assessing the risk and the nature of the uncertainties involved.
2. For major systems, the DSARC and its counterparts in the Services can require explicit answers to such questions, either as part of the supporting staff work prior to decision, or as part of brief sections in or annexes to the

TABLE III-28. APPLICABILITY OF POTENTIAL MANAGEMENT ACTIONS,
BY CLASS OF SYSTEM

Potential Management Action	Applicability of Action			
	Class I	Class II	Class III	Class IV
1. Improvement of electronic components/subsystems within system generation	Yes ^a	Yes	Yes, class supports action	Class consists of components or devices for independent use
2. Decoupling of development and IOC schedules for platform and electronics	Yes ^b	Yes	Yes, implicit	Class consists of components or devices for independent use
3. Improvement of visibility, to management, of potentially cost-driving subsystems of major systems	Yes	Yes	Management level must be lower than DSARC or its equivalent in Services	Must be at lower level and selective
4. Allowance for technological and cost uncertainties	Yes	Yes	Yes	Yes
5. Iteration for user-producer requirement review	Yes	Yes	Yes	Yes

^aApplies primarily to components if system is almost wholly electronic.

^bIn many cases, platform exists only to carry electronics.

- DCP. This would require that the DCP identify the key electronic subsystems (see option 6, below).
3. Since the DSARC and comparable bodies do not ordinarily review acquisitions of Classes III and IV, it may be considered desirable to establish similar panels at lower levels of management in the OSD and the Services for this purpose. Since review already takes place in individual offices (e.g., R&D, I&L, comptroller), this would simply increase coordination of such reviews. The large number of Class III and Class IV acquisitions suggests the necessity for establishing threshold criteria for such review, at least for Class III. Examination of line items such as those in Table III-26 indicates that levels such as \$10 million RDT&E or \$50 million procurement might be appropriate, but a final determination would depend on careful analysis of the budget and project structure to limit the number of systems above threshold to something manageable. These systems would be treated in this form much as major systems are treated.
 4. The DDR&E Advisory Group on Electronic Devices (AGED)²⁴ has been effective in advising on research in its areas of responsibility. A parallel group for systems could be established to advise on the problems of the large number of Class IV acquisitions.
 5. To ensure iteration of requirements decisions and value judgments as development experience is gained, thresholds of departure from the initial requirement could be established, beyond which mandatory review by the cognizant Service or OSD (as appropriate) would be required. The DSARC or other cognizant OSD office would be kept informed when the Services undertake such reviews. The thresholds established could still permit requisite latitude for change on the part of the program manager--they might allow, for example, any or all of: 10 percent development or production

cost increase; 10 percent reduction of specified performance parameters; and IOC delay of a year. The key questions in subsequent review would be: whether the departures noted presaged further departure from the initial requirement; how much; and whether, in view of these changes, the formal requirement should continue to exist, or whether development should be stopped or redirected.

6. Since it is difficult for top-level management to monitor the details of a process as complex as that attending the establishment of requirements and the approval of acquisitions, the OSD and the Services may find it desirable to bring the responsibility and authority associated with the important aspects of such monitoring into better focus. This could, for example, be accomplished by an office or an individual responsible for obtaining agreement on definition of electronic subsystems to be singled out for special attention, and for making certain that the need for reviews such as those discussed under option 5, above, is brought to appropriate management attention. This point of responsibility could also be alert for opportunities to consolidate like subsystem or equipment requirements for several systems.

It should be noted that these suggested options for closer management attention to electronic systems apply to intended acquisitions only--those systems that are to be procured or that enter development with relatively firm procurement plans in view [in DOD terms, the sequence from advanced development (6.3B) through engineering development (6.4)/operational systems development (6.6)]. Many systems or components may enter exploratory development (6.2) or advanced development (6.3A) with the idea of developing technology or testing feasibility. Too-tight management control in these phases is undesirable if it will stifle initiative that may make new kinds of systems available.

6. Findings and Recommendations

a. Findings

- A requirement for a system or subsystem may be defined as including performance, physical characteristics, cost, quantity, and schedule--all in conformity with a statement of threat or need. While the overall requirements and acquisition decision process includes attention to all these components, the current approach to establishing a requirement tends to start with desired performance and characteristics. Cost, quantity, and schedule are modifiers, added later. Thus, requirements tend to be performance-driven, with inadequate early consideration of pragmatic essentials.
- The requirements and acquisition decision process includes, at least formally, the attributes necessary for effective management of system acquisition. In actual implementation, however, cost-driving aberrations of the process occur at several stages: in establishing the original requirement and in expanding it into system characteristics and specifications; in the interactions between management practices and advanced technology; in cost estimating; and in contracting practices.
- Costs of progressions of wholly new-generation weapons systems have increased much faster than costs of progressions of product-improved systems, even when the product improvements have involved incorporation of new generations of electronic subsystems. This suggests that cost savings would result if, in establishing requirements, within-generation system improvements were favored over totally new-generation developments, where that is feasible within the uncertainties of threat or need. The additional costs of new-generation systems appear to arise partly from trying to drive new vehicle, engine, and electronics developments

all to the same schedule, and partly from the engineering difficulties in achieving compatibility among all three when none of them is yet defined well enough to permit prediction of the interactions when they are combined. This suggests that cost savings could be achieved if electronics IOCs were established separately and independently of vehicle IOCs, when feasible, and the electronic subsystems were independently developed. The specification of form, fit (interface), and function requirements for the electronics is essential to such independent development. Independent development would make possible the consolidation of requirements for like electronic subsystems and equipment and would broaden the applicability of specific designs to several systems.

- Other important aberrations of the requirements process leading to cost growth include: selection of desired operating points too high on the cost-performance curve; failure to allow for uncertainty in selecting the operating point; cascading of detailed requirements between the decision and detailed implementation levels; and failure to iterate requirements decisions as development experience is gained.
- There is insufficient visibility, at top management levels, of potentially cost-driving electronic subsystem problems.

b. Recommendations

- ★★★ In exploring and establishing a system requirement, give performance, physical characteristics, cost, quantity, and schedule equal status from the beginning, and perform trade-offs among these early in the game.
- ★★★ In major system developments, separate vehicle IOCs and electronic subsystem IOCs where possible, and develop the

★★★ Highest priority; ★★ high priority; ★ priority.

electronics independently. Consolidate like subsystem or equipment requirements wherever feasible.

- ★★★ Increase visibility to top-level management of potentially cost-driving developments of electronic subsystems associated with major systems by instituting suitable review prior to each DSARC review. As appropriate, provide for a similar visibility to management of developments of less-than-major electronic subsystems and equipments by refocusing reviews to make them analogous to DSARC review, but at lower management levels.
- ★★★ Give increased consideration to product-improvement programs as a means of fulfilling new requirements, as opposed to institution of wholly new development programs.
- ★★★ Select technology and performance objectives for new developments conservatively (i.e., low on the cost-performance curve), except in cases where military necessity imposes an overriding need for risk-taking to achieve extremes of performance. Allow for uncertainty in establishing the corresponding system requirements.
- ★★★ Iterate requirement and acquisition decisions if performance, characteristics, cost, quantity, or schedule depart significantly from initial plans during development. Establish criteria to trigger such iteration.
 - Wherever possible in light of threat or need uncertainties, intensify the practice of choosing within-generation system improvements in preference to wholly new-generation system developments.
 - Make certain that contract structures neither inhibit tradeoffs by the DOD between cost and other requirements components nor drive cost-increasing requirements when that is unintended.

★★★ Highest priority; ★★ high priority; ★ priority.

Some potential management options for implementation of the above have been discussed in Section III-B-5. These involve: issuance of additional management guidance; provision of subsystem information in conjunction with the DCP/DSARC process; focusing of review of less-than-major systems, and appropriate management arrangements for such review; establishing thresholds of departure from planned requirements and iterating the requirements review in case of such departure; and focusing authority and responsibility to help ensure adherence to the new guidance and procedures.

C. DESIGN TO COST

Poor man, said I, you pay too much for your whistle.

--Benjamin Franklin

1. Initiation of the Concept

DOD Directive 5000.1¹³ established the current broad policy on procedures to control costs of major systems acquisitions. The Services subsequently published their own guidance letters regarding cost control in system development and acquisition.²⁵ The Army covered the concept in some detail while the Air Force and Navy described it in more general terms. In view of the known successful implementation of design-to-cost procedures in the commercial sector, the broad policy guidelines could be considered sufficient to permit each Service to embark upon procurements embodying design-to-cost principles. Dr. John S. Foster, Jr., then Director of Defense Research and Engineering, in an address²⁶ before the National Security Industrial Association on March 12, 1970, described the new approaches to be taken to the procurement of new weapons systems. Where heretofore performance at any cost might have dominated the systems acquisition process, it must now be realized "...that price has as much priority as performance." It would, therefore, be necessary "...to make cost a principal design parameter." Since that time the concept has undergone further evolution, and it has been more firmly adopted as a basic precept of the DOD weapons systems acquisition process.

While the design-to-cost (DTC) concept had, and retains, some ambiguities, it includes the following basic practices and procedures:

1. Cost should consciously be made a design parameter, equal in status to performance and other system specifications.
2. Performance can and will be given up and IOC will be deferred, within limits, if necessary to hold cost down.
3. A DTC goal or target should be designated early in the acquisition cycle, preferably prior to the beginning of the development effort or very shortly thereafter.

4. Competition should be incorporated and maintained up to and, where feasible, through production, as a means of holding costs down and holding open the Government's options to acquire lower-cost equipment.
5. DTC performance should be monitored throughout the acquisition cycle, to ensure timely visibility of significant variations from target costs and performance.

What cost is meant in the DTC concept? Most often, the meaning has been taken to be unit production cost. R&D might be increased to achieve lower unit production cost.²⁷ The cost target can also be unit flyaway cost²⁸ (and is so specified in a memorandum on the subject from the Deputy Secretary of Defense), program cost, or life-cycle cost, which can be defined in various ways. Life-cycle cost is, in view of the uncertainties discussed in Section III-A, extremely difficult to forecast or even to estimate a posteriori. The use of warranties or other forms of contractor maintenance, where feasible, would, as discussed in Section IV-A, give a firmer estimate for the bulk of the life-cycle costs from development through maintenance, the remaining uncertainties being associated with the Government's administration and management costs and some operational costs.

The establishment of a cost target for any system is, as yet, an uncertain procedure. It involves implicit or explicit assessments of the value of spending a certain amount of money to achieve a certain performance. Comparison with a civilian equivalent of the equipment, where possible, may help establish a reasonable cost goal. In other cases, it has been possible for DOD to work with industry via the proposal process to ascertain likely magnitudes of cost to achieve desired performance. Finally, in many cases, all judgments and experience appear to join in a consensus that some selected cost goal for a system appears reasonable, or is of an "acceptable" magnitude.

2. Potential Problems in Design-to-Cost

Several recent analyses have pointed out the difficulties that may be encountered in DTC.²⁹ Some of them are worth enumerating briefly, as

background for consideration of DTC efforts by the Services in the electronic subsystem area.

The key problem, interacting with the difficulty of establishing a reasonable cost a priori, derives from the concept of reducing performance requirements, if necessary, to achieve a desired cost. Performance requirements can obviously be reduced to the point of unacceptability. Since the validity of the target cost is initially uncertain, the target cost cannot necessarily be held sacrosanct over all other design parameters. Thus, the flexibility to let cost increase or to let schedule slip is also required. The choice of performance goals high on the cost-performance curve (Fig. III-11, p. 145), which is frequent for defense systems, reinforces this need. Additional related difficulties include: inability to specify the size of buy early enough to allow contractors to make an accurate estimate of costs; the requirements pyramid (Table III-22, p. 148) and the hidden potential costs it implies; inhibition of the program manager in making tradeoffs on performance specifications considered mission-critical; inhibition of the contractor in arriving at an optimum design because of overconstraining specifications; and difficulties arising from the contracting process.

Within the ASPR, this investigation has found, there are no specific constraints that need inhibit the flexibility necessary to achieve DTC goals. However, a number of practical problems must be resolved. These include the following three:³⁰

1. Ordinarily, in the evaluation of proposals, the technical proposal and the cost proposal are separated so that consideration of one will not influence consideration of the other. Obviously, if a contractor is to design to a cost and have freedom to interchange cost and technical performance, both aspects of his proposal must be considered together. This requires a change in a practice of long standing.
2. The contractor must have the freedom to vary the internal configuration of a design to try to achieve a desired cost. If the

Government prescribes the design in minute detail, the contractor cannot be held legally responsible for the cost outcome.*

3. It is difficult to hold a developer responsible for future costs if life-cycle cost is the basis for selection. Analysis of the legal problem indicates that during development the target production cost has no contractual relevance other than as a design objective. Otherwise, it would represent an attempt to hold constant a variable that is dependent upon later decisions about the values of certain performance levels. Since cost as well as performance may have to vary during development, a degree of uncertainty is imposed that cannot be removed during the total duration of the development contracts but only during the production contract. An attempt to invoke a promise of future performance covering the target cost would fail under Section 1-334 of the ASPR, which prohibits the use of total package procurement or production options for systems not yet developed.

The difficulty of establishing enforceable unit production or flyaway cost targets during the development phase, as well as the potential need to allow development costs to rise to enable design for lower production costs, argues for a phasing of the cost targets in keeping with the phasing of the acquisition itself. At least, separate development and production (or flyaway) cost targets are indicated, with production cost fixed (it may be set provisionally earlier) only after the development part of the cycle yields a clear idea of the potentially and realistically achievable production cost. Even at this point, early production experience may show that further changes in design would help reduce production costs and increase reliability further, suggesting a resetting of the production or flyaway cost target after low-rate initial production (LRIP) for systems that are to be procured in quantity. This would be consistent with the notion, discussed at other points in this report, of maintaining competition through production.

*Military Standards could have this effect and can, therefore, be in conflict with DTC acquisition (Sections IV-B, D).

Assuming DTC acquisitions can be achieved successfully, the DOD would also face certain operational difficulties. Special requirements for military use may mean added functions or environmental constraints and may, therefore, increase the cost of equipment that might otherwise be comparable to civilian equipment. Thus, the Government may not always be able to reduce costs by acquiring technology from the civilian economy. If the program manager and the contractor can make changes in performance to stay within the target cost, the user faces uncertainty about achievement of the performance he originally deemed necessary, with a radiating impact on other systems and the operational quality of his force. If internal configuration can be varied to hold costs down and to rectify maintenance and reliability problems, successive production buys of a component or system may differ sufficiently to complicate logistics.

Thus, if DTC is pursued to its logical limits and across the majority of acquisitions, structuring of overall force performance capabilities around what can be achieved for a given amount of money will be necessary to a much greater extent than was true in the past. Especially in electronics, DTC implies that there would have to be more reliance on proven technology (including advanced proven technology, used to reduce costs) and avoidance of the initial costs of technological advances (i.e., operating points low on the cost-performance curve would have to be chosen). In a consequent DOD reliance on the civilian economy for technological advances, those advances might come slower than the DOD desires or feels is necessary. Conversely, the cost of technological advance, if the DOD wishes to press it, must necessarily be high in electronics, since DOD electronic developments and procurements represent but a small (and declining) fraction of the total market (Section II-J, p. 64). Thus, DTC in electronics implies greater proliferation of military equipment designs using commercially standardized parts within specially designed "black boxes," so that the black boxes themselves will have to be standardized in form, fit, and function for use in diverse applications or for incorporation in successive generations of major systems (p. 143). The resulting logistic complexities may make it more economical for the DOD either to return components to manufacturers to repair, or to replace rather than

repair electronic devices or components at some level of complexity. The economic tradeoffs involved remain to be worked out.

From all the above, it is clear that the DTC concept is still in its infancy, especially for DOD electronic equipment. Much remains to be learned through experience, with long-term implications for the military force structure and the DOD ways of doing business. For most reasonably advanced systems (which most defense systems are), both cost and performance are likely to have to be adjusted during the DT&E phases of DTC programs. When the cost goes above that planned, it will be difficult to demonstrate that this higher cost is still below the cost that "would have been otherwise." That is, it will be difficult to measure success. However, success in the production phases will be easier to measure, since by then the unit production or flyaway cost will probably have been fixed. This also argues in favor of unit production or flyaway cost as the principal DTC target.

3. Commercial Comparability; Competition

As a number of recent DOD advisory groups have pointed out,³¹ designing to a predetermined cost has been a way of life in the commercial sector. Although it is difficult to generalize, a number of practices (performed with varying degrees of success) appear to be inherent in the civilian industrial sector:

- Market surveys to estimate the potential sales of new products or improved existing products
- Setting of cost targets based on estimated consumer demand and effects of competition
- Continuous tradeoffs of performance against cost to ensure a match between (a) the characteristics and price of the product and (b) estimated demand and demand elasticity
- Periodic involvement of top management in general decisionmaking while maximum freedom is granted to program managers in daily operations

- Close coupling of engineering, manufacturing, and financial personnel
- Consumer testing of early prototypes of a product
- Continuous feedback of field data to design engineers, to continue cost-performance tradeoffs and competition throughout the production life of a product
- Where appropriate, the use of guarantees, warranties, or factory-qualified maintenance.

While many of these practices can be applied to DOD acquisitions of components and systems, important differences must be accounted for. Among these differences are the following:

1. Motivation. Commercial industry is oriented toward profitable sales. Very often a product is changed to improve its physical characteristics (for example, its weight and size) and other "attractiveness" features while its performance requirements remain the same. This is true for products that have been on the market for many years, such as radios, and for products recently introduced, such as the four-function, hand-size electronic calculator. A wholly new product must show promise of being able to stimulate a demand sufficient for profitable sales at a price that matches both its producibility and some estimate of its "value" to consumers. The DOD, on the other hand, needs to match equipment performance to a perception of a future threat or military need, that perception being based on estimates of the capabilities of the armed forces and technologies of other countries. Thus, although both civilian and defense planners must work against certain "market" criteria and predictions, it can be argued that the defense planner has less control over the decision as to what and whether to produce in the area of new "products."
2. Economics of the market place. In industry, the break-even point (in time and numbers) for a product can be variable. If market

analysis shows that a product must sell for a certain price and the design of the product requires costs higher than those initially planned, industry has the freedom to shift its break-even point and intensify sales effort to try to capture a larger part of the market. A company's development and production budget may be fixed in any year, but, depending on the financial prospect for the product, plans can be made to use budgets two or three years ahead. The DOD, on the other hand, usually structures a force within a budget that is allocated to it annually by external organizations in the executive and legislative branches. The DOD must pay the cost of the numbers of items it needs from the budget. The flexibility here is to reduce force size if costs increase. Force reduction is often rationalized by showing that the smaller, higher-cost force will have an overall capability that compensates for its reduced size. This sort of rationalization is an uncertain substitute for the relative precision that comes from successive profit measurements of a company's performance in the civilian sector.

3. Management controls. In industry, while top-level management can intervene to change the direction of product development and production, program managers and intermediate managers are judged mainly by sales and profits. The DOD, on the other hand, is accountable to the Congress for how appropriations are spent. The Congress, no less than DOD management, is concerned about performance requirements for major systems, and it must decide whether to allocate money for those systems based on its judgment of the value of the planned performance increment relative to the threat or need, as that threat or need is perceived and judged from uncertain forecasts derived by several agencies. Obviously, political connotations are also of importance in such collective decisions.

Thus, industry's accountability is based on output performance measures, while the DOD's is based on input--what is done with the money given it. Output, for the DOD, can be measured

only when the military forces are used in conflict or deterrence, and then those who provided the forces may no longer be responsible for their performance.

In industry, the design team is free to modify configurations to meet cost targets. There are relatively few specifications and standards; those that exist are ordinarily promulgated by professional or industrial associations and accepted voluntarily. To support its accountability for the expenditure of public funds, the DOD has promulgated strict and detailed specifications, constraining industry in designing the details of systems and components. The DOD also desires these specifications to simplify logistic support and to ensure that equipment will work in severe environmental conditions.

Because of the relative nature of the constraints, commercial practice more easily permits concentration of authority, with freedom for program managers to adapt to the needs of the market as they see them. In the DOD, on the other hand, there is great diffusion of authority because of the diverse review channels and levels of management entailed in overseeing the expenditure of appropriated funds.

Another important area, characteristic of the commercial world and considered important for DTC, is competition. It is generally accepted that during the design and development phase of a DTC program the developer must have genuine freedom to adjust the evolving design to meet the specified target cost, or to adjust the two together to achieve desired force objectives. The military project manager and his industrial contractor must work together in this iterative process by reviewing and modifying cost, schedule, and performance requirements when they are found to conflict with what is technologically realizable within the desired production cost limits. Development, production, and operating costs can be balanced in the same way.

Ordinarily, if there is but a single developer, incentives to meet the cost target may be lacking. Moreover, the use of cost-reimbursement

contracts for the development phase, generally considered desirable for DTC developments, could also encourage prolonged and unnecessary development effort by a single developer. The flexibility permitted the developer implies (as has been noted in another context) uncertainty about the ultimate design outcome. If, at the completion of the development program, the production bid is above the previously desired target cost or if the design is less than satisfactory, and if there have been no competitive developments, the military manager has no alternative developer to whom to turn within the time allotted for development (that is, the time at whose expiration it has been judged the new component or system is needed). Thus, in general, it has been agreed by diverse study groups that the use of competing developers would provide greater incentives to each to complete development on schedule, meet or reduce production cost targets, and provide the best possible design within the cost constraints. Such competition would, ideally, enable the military manager to compare designs and actual production price bids prior to selection. This study has uncovered a number of such instances.*

The way competition is used must, however, depend on the kind of system and its cost. Some major developments, such as a defense navigation satellite system, a major advanced aircraft system, or a major ship, may be judged to be too large for the Defense Department to pay for even two competing prototypes. Yet it is in exactly such huge programs that competition may prove beneficial. Experience such as that with the C-5A and the F-14 has shown that when the cost of the development is larger than the net worth of the developing company, and in the absence of competition, the unhappy option most often open to the Government is that of either continuing acquisition of the overly expensive system after it is developed (probably in reduced numbers) or canceling the acquisition (possibly bankrupting the contractor). Then the issue becomes political, since the employment of thousands of people and the health of a section of the economy are at stake.

*E.g., AWACS, AIM-9 series, PAVE SPIKE pods.

Nevertheless, even when the Government feels that it cannot support direct competition, other choices representing indirect competition may be available. For example, a military adaptation of a commercial system (say, in computers) may be available. Moreover, competitive development and procurement could still be applied to many subsystems and components of such major systems. In addition, procurement and management problems, and the implications of competition, will vary according to whether the Government is acquiring high-technology systems that are few in number, such as communication satellites and related systems, or whether it is acquiring a large number of relatively inexpensive systems or components, such as troop radios.

It is apparent that these variations will interact in a complex way with the problems of using competition and providing options. Success of competition in the civilian economy is measured by sales and profits. Moreover, one of the welcome outcomes of competition in the civilian economy is a diversity of products. In the DOD, the impact of competition is more difficult to measure (Section III-F).³² While the data show advantages after certain points in the acquisition process are reached (e.g., kinds of systems, size of development, size of production buy when competition is introduced), there are countervailing costs. Research and development may cost more unless industry is motivated to increase its share of these costs; competition through production may incur the cost of the reprourement data package; gains from the "progress" or "learning" curve may be achieved early, with less subsequent benefit from larger production runs; and the DOD as a whole will incur the possible cost of a more complex force if the diversity of designs of systems or components to accomplish a specific military task is increased.

4. Current Applications of Design-to-Cost Programs

In July 1972, DDR&E requested that the Services select appropriate electronic subsystem procurements that could be used as DTC experiments. Accordingly, ten programs, listed in Table III-29, were nominated by the Services. In addition, in early 1973 a number of major systems were designated as DTC system acquisitions (Table III-30). Subsequently, a

memorandum by the Deputy Secretary of Defense³³ initiated the process of establishing DTC goals for all major DSARC programs that had not yet reached "milestone III." In this memorandum the cost to be "designed to" was specified as the average unit flyaway cost. The memorandum authorized the Services and program managers to make adjustments in performance and schedule necessary to achieve the cost goals. It also initiated a mechanism for reviewing contractual provisions that would have to be changed to achieve this. All future programs are to have, as early as possible and not later than the beginning of full-scale development, an estimate of the cost to be designed to.

Although the major-system DTC efforts will be observed by management in its efforts to hold costs down, systematic observation of major-system programs for analysis of problems, successes, and failures will be difficult. By definition, major systems are large, expensive, and important. As a consequence, their progress is a sensitive matter and they are difficult to monitor with the primary objective of learning. However, the subsystem experiments do not present these problems and, therefore, represent an opportunity to experiment with DTC acquisitions in the electronic subsystem area. The subsystem DTC experiments have, therefore, been examined in some detail as part of this study.

TABLE III-29. PROGRAMS DESIGNATED BY THE SERVICES
FOR DESIGN-TO-COST EXPERIMENTATION
IN ELECTRONIC EQUIPMENT ACQUISITION

Army

Absolute Altimeter (AN/APN-209)
Helicopter LORAN (AN/ARC-114)
Lightweight Doppler Navigation System (Helicopter)
Low-Cost FLIR

Navy

Low-Cost Ship EW Suite
Airborne Radar (WX Series)
Advanced Airborne Digital Computer (AADC)

Air Force

Airborne TACAN (AN/ARN-XXX)
Tactical UHF Command Radio (AN/ARC-XXX)
Medium-Accuracy Inertial Navigation System (MICRON)

TABLE III-30. MAJOR-SYSTEM DESIGN-TO-COST PROGRAMS^a

Army

1. Man-Portable Air Defense (MANPAD) System
2. Armored Reconnaissance and Scout Vehicle
3. Utility Tactical Transport Aircraft System (UTTAS)
4. New Main Battle Tank (MBT)
5. SAM-D
6. Advanced Attack Helicopter (AAH)

Navy

7. AGILE Missile
8. Patrol Frigate
9. PHALANX Missile
10. Patrol Hydrofoil Missile Ship
11. AN/BQQ-5 Submarine Sonar
12. AIM-7F Missile
13. VSTOL Technology Prototype

Air Force

14. AX (now A-10) Close Air Support Aircraft
15. Lightweight Fighter
16. Advanced Medium STOL Transport
17. Low-Altitude Supersonic Target Drone

^aSource: Ref. 34.

5. The Subsystem Design-to-Cost Experiments

Table III-31 shows the timetable for these experiments. Table III-32 summarizes the salient features of the experiments according to postulated desiderata for DTC programs emerging from the above considerations.³⁵

From Table III-32, it can be noted, first, that three of the ten designated programs are not currently, or are not yet, formal design-to-cost programs, as discussed in the relevant DOD sources. Rather, they are programs in which cost is receiving more emphasis than it might otherwise have received. One of these projects results from an attempt by industry to design a radar to a specified cost, using the freedom to trade performance for cost that would be needed in DTC programs; it is not clear yet whether DOD will find the product useful and acceptable. When it is more firmly defined, another of these programs, the Army FLIR program, would

provide potential candidates for DTC contracts on the very large procurements (several hundred million to a billion dollars) that will be in the offing.

TABLE III-31. SCHEDULES OF SUBSYSTEM
DESIGN-TO-COST EXPERIMENTS

<u>Service and Program</u>	<u>Target Date(s)</u>
<u>Army</u>	
Absolute Altimeter (AN/APN-209)	19-month engineering development, fall 1973 to spring 1975.
Helicopter LORAN (AN/ARC-114)	Engineering development and test completion mid-1975.
Lightweight Doppler Navigation System (Helicopter)	Engineering development completion mid-1976.
Low-Cost FLIR	Testing of various models between mid-1974 and mid-1978.
<u>Navy</u>	
Low-Cost Ship EW Suite	Schedules are part of competition; initial design phase begun January 1973.
Airborne Radar (WX Series)	Indefinite.
Advanced Airborne Digital Computer (AADC)	Completion of most hardware early 1976; completion of various segments of software 1976-1977.
<u>Air Force</u>	
Airborne TACAN (AN/ARN-XXX)	14-month engineering development, beginning mid-1973.
Tactical UHF Command Radio (AN/ARC-XXX)	9-month development RFP issued July 1972; development not completed.
Medium-Accuracy Inertial Navigation System (MICRON)	12 final system prototypes plus testing by spring 1976.

A

B

			Sa:
			Cost and Technology Evaluation Linked to Contract Selection
Service and Program	Performance Sought	Target Cost and Basis	
<u>Army</u>			
Absolute Altimeter (AN/APN-209)	Minimum altitude range, accuracy; frequency; size; RAM. Others "desired."	\$3500 unit production cost (max); 2000 units; 90% LC; LCC considered for production.	No
Helicopter LORAN (AN/ARC-114)	Minimum performance specified.	\$20,000 unit production cost for 2000 units; 87% LC; LCC considered.	No
Lightweight Doppler Navigation System (Helicopter)	Based on available UK and Canadian prototypes.	\$20,000 unit production cost for 500 units.	No
Low-Cost FLIR	Modular FLIR developments being considered for missile and weapon sights, combat veh. Not yet formulated as DTC program.		
<u>Navy</u>			
Low-Cost Ship EW Suite	Cost-phased modular suite; contractor to specify performance achievable at five cost levels.	Navy suggests unit, installation, and R&D costs based on Phase I proposals.	Yes
Airborne Radar (WX Series)	Modular, multipurpose radar family.	A contractor-developed series of radars designed	
Advanced Airborne Digital Computer (AADC)	General-purpose modular central computer, 1978-1990.	None specified <u>a priori</u> .	No
<u>Air Force</u>			
Airborne TACAN (AN/ARN-XXX)	Minimum performance specifications, 1000-hr MTBF required.	\$10,000 unit production cost for 500 units; life-cycle cost index for production competition.	Yes, but not at first
Tactical UHF Command Radio (AN/ARC-XXX)	Replaces two other radios; 1000-hr MTBF.	None specified; production award to lowest LCC bid.	No
Medium-Accuracy Inertial Navigation System (MICRON)	Medium accuracy; light weight; small; 2000-hr MTBF; nuclear hardness.	\$35,000 unit production cost for 500 units; LCC considered, not specified.	Sole-source

B

TABLE III-3

Target Cost and Basis	Salient Contract Features			Other Features		
	Cost and Technology Evaluation Linked for Contractor Selection	Freedom to Trade Off Cost/Performance/Schedule	Government Options for Buy	Warranty	Standardization and Specifications	Incentives
Unit production cost (max); 90% LC; LCC considered.	No	Some (excl. schedule)	5000-10,000 units ultimately	Option	Conventional	CPAF
Unit production cost for 87% LC; LCC considered.	No	Yes	LRIP plus production	No	Conventional	CPIF (development only)
Unit production cost for 87% LC; LCC considered.	No	Not yet defined	Not yet defined	Not yet defined	Not yet defined	Not yet defined
for missile and weapon sights, combat vehicle driving and fighting, aircraft flight and fire control, and ground observation.						
Suggests unit, installation, and costs based on Phase I proposals.	Yes	Yes (priorities assigned)	Flexible, for many or all ships	Option; also contractor maintenance option	Conventional	Left to contractor proposal
Contractor-developed series of radars designed to a particular price for various functions and performance. Navy is considering.	No	No	Not yet decided	No	Conventional	FP
Unit production cost for 87% LC; life-cycle cost index production competition.	Yes, but not at first	Yes, Program Office	0-9000	Option for 2 yr, with 2 renewals	Form-fit-function	CPIF
Specified: production award bid.	No	No (reliability paramount)	0-7000	No, Air Force maintenance	Conventional	FP/AF
Unit production cost for 87% LC; LCC considered, not bid.	Sole-source	Yes (excl. schedule)	Estimated 5000-10,000, including all sources plus civil	Option	Not set	CPAF

C

TABLE III-32. SUMMARY OF EXPERIMENTAL DESIGN-TO-COST DEVELOPMENTS OF SUBSYSTEMS

<u>Features</u>		<u>Competition, Actual or Planned</u>				<u>Remarks</u>
<u>Standardiza- tion and specifications</u>	<u>Incentives</u>	<u>Pre- Development</u>	<u>During Development</u>	<u>Pre- Production</u>	<u>During Production</u>	
Conventional	CPAF	Yes	Yes	Yes	No	Contractor maintenance option, post-warranty.
Conventional	CPIF (development only)	Yes	Yes	Yes	No	Originally not a DTC program.
Not yet defined	Not yet defined	Yes	Not yet defined	Not yet defined	Not yet defined	Engineering development RFP currently being formulated.
Control, and ground observation to consolidate many developments and to reduce total cost.						
Conventional	Left to contractor proposal	Yes	Yes	Yes	No	Contractor to install modules on platforms for Navy test of operation, operability, documentation.
Performance. Navy is considering flight test and evaluation program to test performance and RAM.						
Conventional	FP	Yes	Yes	Yes	Not decided	Not formalized as a DTC program.
Form-fit-function	CPIF	Yes	Yes	Yes	Maybe	Arinc-type specifications.
Conventional	FP/AF	Yes	Yes	Yes	No	Model for test required with proposal. Arinc advice sought on testing and selection.
Not set	CPAF	No	No	No	No	Based on company-funded start. Other contractors to help monitor and prepare data package.

Of the remainder of these programs, all but one involve competition through development, but few or none will carry competition into procurement. The problem of judging the contractors' proposals on the interplay of technical performance and cost is apparently not yet broadly solved--it has been possible to have a single evaluation team consider the cost and technical proposals together in only two of the cases listed. Most of these programs use unit production cost for a buy of a particular size as the target-cost criterion, but the planned buys in all cases are very much smaller than the total number of equipments that will ultimately be needed and that may be purchased. Thus, although production is not generally intended for competition in these programs, a contractor might still find it possible to make a very low bid in hopes of gains from later, much larger production. On the other hand, a number of the programs (e.g., UHF radio and others with incentive contracts) contain specific penalties for contractors who do this.

In half of these programs life-cycle costs will be considered in the production contract award, but it is not yet clear whether the basis of calculation of life-cycle cost will be accurate enough for fair comparative judgments. Most of the programs provide for a warranty option, and some require a contractor estimate of the potential cost for a maintenance contract. Thus, the combination of life-cycle cost, warranty, and maintenance contract estimates may, in a few cases, give some basis for judging the contractors' view, prior to production and in some cases early in the development cycle, of the impact on maintenance and reliability of the DTC approach in these programs. However, it is not clear that any actual warranty or contractor maintenance experience will be gained, since in all cases there are only options.

All the programs offer at least some flexibility to trade off some or all of performance, cost, and schedule. Sometimes the program manager has this flexibility; sometimes he must refer to a higher authority. But many of the performance requirements are "hard," and these could either constrain the tradeoffs in unanticipated ways or be found to drive costs, posing the kinds of requirements/cost exchange problems discussed earlier. In only one program (the Navy electronic warfare suite) can it be said

that the potential contractors have simply been told what the job is in functional terms, given a statement of the relative importance of all the performance and cost factors, and left to see what they can accomplish competitively in making all of the tradeoffs among cost, performance, schedule, characteristics, and quantity. In this program, the potential contractors are also free to suggest the type of contract they believe they can best work with. In only one program (the TACAN), form-fit-function standards are specified and the Arinc approach to general specifications is taken. Most of the contracts involve some form of award or incentive fee, which, in some of these contracts, is based on the difference between predicted and experienced production and life-cycle costs. None, however, appears to permit the contractor to save money in development and production, using the difference between the lower cost level he achieves and the agreed-upon cost level as an incentive to cost reduction.³⁶

It is apparent from the above observations that these ten programs do not represent a controlled "experiment" in which all or most of the important variables are identified and varied systematically and in which there are enough like developments to test the statistical significance of results. Practically, such an experiment would be difficult. Even in these ten programs, however, many of the important management variables will be observed, and in most cases for more than one acquisition. These include the effects of: competition (up to production); ability to adjust performance somewhat to hold to set costs; ability of the Government to preserve its options; the possible use of warranties; and a small number of variations in contract incentives. Thus, something will be learned from these programs. It may even be possible and desirable, in programs where the potential outcome seems uncertain, to take specific courses of action explicitly to explore the potential consequences.

Nevertheless, these experimental programs are so few, and the experience they provide is likely to be so variable, that their successes or failures will be difficult to generalize. This difficulty can be alleviated by adding to the number of experimental programs. A large potential field for observation is available from the numerous Class III systems developments (Section III-B-4, p. 155).

Note that a number of variables are not or may not be observed in the present ten experimental programs. These include: competition during production; variation of standards and specifications; freedom to vary all five components of a requirement (p. 128); forms of contracts other than those offering incentive or award fees; and a wider, more representative sample of total system or equipment costs. These variables could be made elements of some of the additional programs selected for experiment.

Overall, around 30 programs should not be too difficult to monitor and should give more varied and useful data for later application.

It must be noted that a considerable amount of time will elapse before all the results of the experimental programs are available (Table III-31). In addition, the kind of systematic observation and variation of conditions being considered here does not yet necessarily apply to major systems or their mission-critical subsystems (Classes I and II). The DOD needs early DTC information for management and needs to know how to extend DTC experience with development of independent subsystems to systems of Class I and Class II, where a considerably greater amount of money may be at stake. Given the time involved, and the size and complexity of the DOD systems acquisition budget, the lessons on DTC will doubtless have to be applied as they are learned, before all the results of the DTC experiments and observations have been obtained and analyzed. By the time the DTC concept and the knowledge to apply it have reached maturity, many changes in philosophy and management may have occurred in the defense environment. Yet, as our discussion of the operation of the requirements process shows (Section III-B), the problems involved in DTC have had considerable longevity.

The ten subsystem programs discussed as DTC experiments above are mainly developments that would have gone forward in any event but were singled out for specific observation, with some added steps in the direction of DTC. This approach has now been extended to major systems as well. In fact, all DSARC-level systems development is now to be managed on a DTC basis. Certain major systems (those listed in Table III-30) were the first major systems started on this basis, and the

management arrangements and many of the decisions affecting them have already been made. They would, therefore, be useful candidates for careful observation and extraction of "lessons learned" for application, together with the "lessons learned" from the ten subsystem DTC experiments, to systems just entering DTC management.

6. Findings and Recommendations

a. Findings

- Design to cost (DTC) in defense systems acquisition is still in its infancy. Among the problems yet to be solved are:
 - How to establish the cost target in view of the lack of an adequate data base and limited cost-estimating techniques.
 - How to resolve the uncertainty for the user resulting from continual cost-performance tradeoffs and their potential effects on force size, capability, and logistics.
 - How to incorporate commercial cost-saving practices in DOD DTC procedures when motivations and accountability are basically different in the two sectors.
 - And how to extend competition through the acquisition cycle, especially for acquisition of large-scale systems and for large-scale procurements.
- Institutional factors, established ways of doing business, and organizational inertia still lead to DTC procurement practices not consistent with the DTC philosophy, such as: provisions for separate evaluations of the cost and the technical aspects of the proposals, thus precluding the requisite tradeoffs; requirements for too early and too detailed configuration control that will interfere with evolutionary improvements; inflexible application of restrictive specifications on materials, parts, processes, and finishes; and various other restrictive provisions.
- DTC developments may be more expensive than traditional developments in which production cost is not invoked as a design parameter.

- Wholehearted implementation of DTC in military electronics implies:
 - Greater reliance on proven technology, with technological advance driven largely by the commercial sector in areas of broad commercial usage.
 - Changed logistics procedures, including more detailed analyses and regular consideration of the alternatives of contractor maintenance or of "zero maintenance" (i.e., throwaway parts or components).
 - Use of interface standardization and the resultant evolution of several competing interchangeable designs, with consequently increased logistic complexity. Such added logistic complexity can be more tolerable if the aforementioned changes in maintenance concepts are implemented.
- The experimental and other major-system DTC acquisitions initiated in 1972 will not be complete in time to provide DOD the experience needed for other acquisition programs in the near future. DOD will, therefore, probably have to attempt to act on "lessons learned" before the "experiment" is completed.
- The ASPR includes no barriers to DTC, but some associated contract implementation practices of long standing must be changed to obtain the full flexibility that DTC requires.

b. Recommendations

- ★★★ Choose easily defined DTC cost targets such as unit production or flyaway costs (rather than, for example, the presently still ill-defined life-cycle costs; but see next paragraph). Establish such targets early, permitting successive revisions during development, contractual commitment to a unit cost for low-rate initial production (LRIP) at the start of LRIP, and another contractual commitment for unit cost at the start of full-scale

★★★ Highest priority; ★★ high priority; ★ priority.

production for systems to be procured in quantity. Flexibility to revise cost targets should decrease and should be based increasingly on firm experience as the development-to-production cycle progresses.

If the equipment is to be maintained by the supplier under long-term warranty, the DTC target can be established as the sum of the production cost and total warranty cost; this sum may be considered a surrogate for life-cycle cost. But if military maintenance is contemplated, establishing life-cycle cost as a DTC target is not now appropriate because of the inadequacy of current knowledge of the cost to the Government of military maintenance, and of the dependence of these costs on equipment parameters.

- ★★★ Establish explicit limits of deviation from "desired" performance/characteristics/cost/schedule/quantity requirements, and authorize program managers to trade off freely among these separate requirement parameters within the established limits. Establish "desired" parameters and permissible deviations such that tradeoffs are in fact possible and not subject to hidden constraints due to technical feasibility, absolute force requirements, or available budgets.
- ★★★ To the extent feasible, maintain design and price competition throughout the acquisition process, especially for components and subsystems.
- ★★★ In the contractor selection process, ensure that performance and cost are considered together rather than evaluated separately.
- ★★ This study identified only one DTC acquisition, namely, the Navy electronic warfare suite, that uses the approach of specifying equipment needs and requirements functionally, leaving it to the

★★★ Highest priority; ★★ high priority; ★ priority.

competing contractors to propose optimal development and production strategies to maximize payoff to both the Government and the contractors, and including maintenance strategies among the variables. More experimentation with this approach should be undertaken.

- ★ Increase the number of DTC acquisitions of electronic subsystems designated as "experimental" for observation and extraction of "lessons learned." Include in these observations the electronic subsystems of the 17 major systems designated as "design to cost" in early 1973 (Table III-30, p. 179). In further experimental DTC acquisitions, seek wider variation of the management variables relevant to DTC (for example, tradeoffs among requirements, program manager's freedom to trade off, competition throughout the acquisition cycle, and different types of contract). The Services should publish "lessons learned" periodically to maximize the pool of explicitly analyzed experience available to all.
- ★★ Review the contracting procedures associated with DTC contracts, modify those that inhibit requisite DTC flexibility, and incorporate the modifications in the ASPR, if necessary.

★★★ Highest priority; ★★ high priority; ★ priority.

D. DESIGN FOR IMPROVED RELIABILITY

The more simple any thing is, the less liable it is to be disordered, and the easier repaired when disordered.

--Thomas Paine

1. General Methodology

In the design of an equipment for improved reliability, the first step is to provide a requirement for reliability, availability, and maintainability (RAM) consistent with mission needs and to translate this into a detailed RAM specification that will meet the needs of the mission while minimizing the cost involved. The cost in this context is the life-cycle cost, embracing both acquisition and O&M costs. Many aspects of the design of systems for high reliability are well known. They include, for example: use of high-quality components; great care in ensuring repeatable processes and high-quality workmanship in the assembly of those components; system design techniques that derate the components so that they operate under conditions less severe than the ones for which they were designed; limited use of redundancy for parts of a system that are particularly prone to failure and that are essential to the function of the system; use of burn-in after assembly of a given part of a system to make sure that infant mortality among components and poor-quality workmanship are exposed during the burn-in periods and are then corrected. During a carefully documented development program on the AN/APQ-113 radar, General Electric³⁷ has found that failures were about one-third due to components, one-third due to workmanship (otherwise known as quality), and one-third due to design. This is fairly typical for a new design. In older designs, failures are usually due mostly to components and quality, failures due to design having been already weeded out.

One other major consideration in designing for improved reliability is design simplicity. There exists a well-known relation between equipment complexity and MTBF: the greater the complexity (measured either in parts count³⁸ or in unit production cost³⁹), the lower the MTBF. It is

important to limit design complexity so that the required MTBF can be attained in practice. The two references cited suggest guidelines for this.

In addition to design features intended to minimize failures, it is essential to give careful consideration in the design process to system partitioning and to the levels of the maintenance organization at which certain repairs are to be carried out. A brief study of an analytical model of an idealized system⁴⁰ suggests that repair costs are least when a system is partitioned into modules of approximately equal cost. The levels of repair can be determined by an analytical procedure, using such techniques as the Army's Generalized Electronics Maintenance Model (GEMM) to compare the cost-effectiveness of various maintenance policies.⁴¹ It often turns out that, over a broad range of the significant parameters, one maintenance policy is distinctly preferable to the others if, for example, the ratio of operational availability to lifetime maintenance cost is used as the figure of merit to be maximized.⁴¹ The validity of such an analysis is predicated, of course, on the validity of the historical data used.

2. Methodology for Reliability Growth

When all is said and done, the usual experience is that when a new design is first assembled, its reliability is approximately one-tenth of what was predicted on the basis of component-failure-rate data.³⁷ The problem then is to structure a "test-and-fix" program which will result in growth of reliability with time. Much of that growth can occur in the plant before demonstration tests to eliminate component, design, and quality defects. To ensure that field-induced failure causes are eliminated, further reliability growth must take place in the field after the equipment has been accepted. It is absolutely essential to have a formal management technique that can be used to ensure that reliability does indeed grow to the specification value before demonstration tests. This can be done by testing and fixing, testing and fixing, testing and fixing. By "fixing" we mean finding the origin of each failure and permanently eliminating it. For example, if a circuit design is faulty, it must be

corrected so as to eliminate the failures that result from it, and if a joint is cold-soldered, the soldering process must be improved. It has been found that when this test-and-fix approach is used and is rigidly adhered to, reliability does indeed grow. In fact, if the failure rate or the MTBF is plotted on log-log paper versus the cumulative test-and-fix time, the plot looks like a straight line. The log (MTBF) increases linearly with the log (cumulative test-and-fix time) at such a rate that its slope is somewhere between 0 and 0.86--usually about 0.5 or 0.6 for a program that has sufficient management attention to ensure that all the necessary fixes are indeed done and that testing is not interrupted too early. This kind of graph is known as a Duane curve. It was first used by Duane of General Electric⁴² in increasing the reliability of a variety of diverse equipments, the curves for which are given in Fig. III-15.⁴³

The Duane curve was later used during development of the AN/APQ-113 radar.³⁷ It provides a very convenient management tool for planning the reliability growth of a new system, since it permits prediction of the growth of system reliability as a function of the cumulative test-and-fix time of the system. It also allows prediction of the cost of the reliability increase if the cost of the test-and-fix time is known. For this, one has to know the cost of testing and the average cost of the fixes usually required (Fig. III-16).

The Duane curve is also an attractive tool for use in monitoring and predicting the field reliability of systems, although thus far it has not been so used. The test-and-fix process can be continued after system deployment to promote the growth of field reliability, but the cost of doing so is, of course, substantially greater,⁴⁴ often by a factor of 10, than the cost of achieving the required reliability before equipment delivery. The cost includes the cost of additional spares that must be present in the supply pipeline during a test-and-fix period, the costs of equipment modification and retrofit, and the less tangible down-time costs for the weapon system in which the electronics is installed.

We must note here the considerable similarity between the NASA philosophy of reliability that requires the complete lot-traceability of

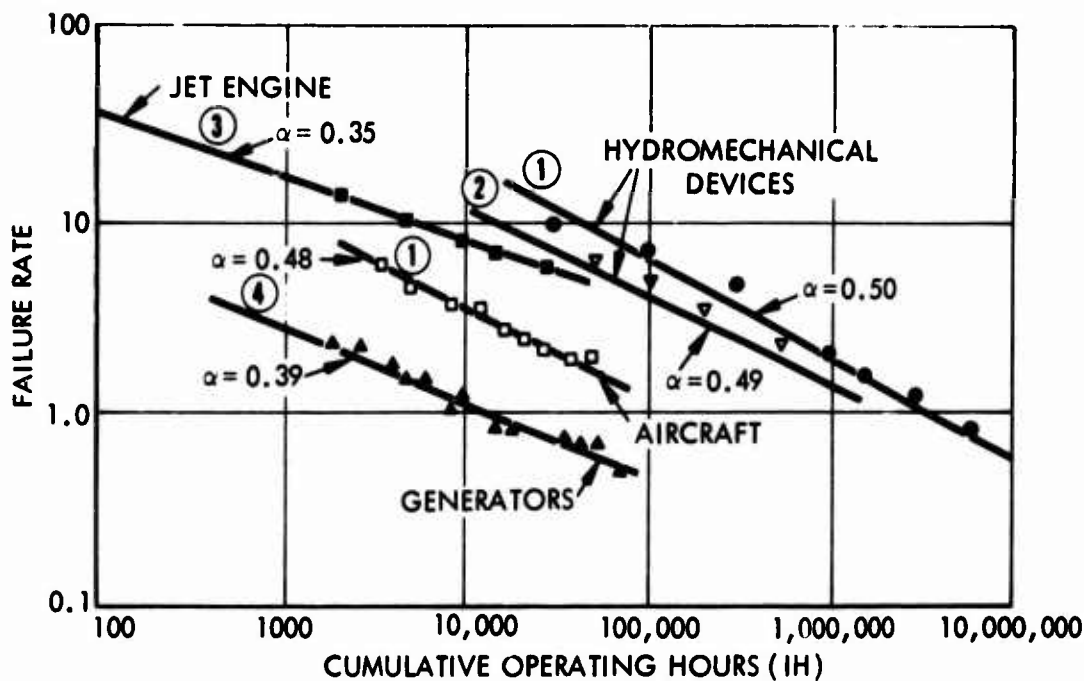


FIGURE III-15. Original Duane Data

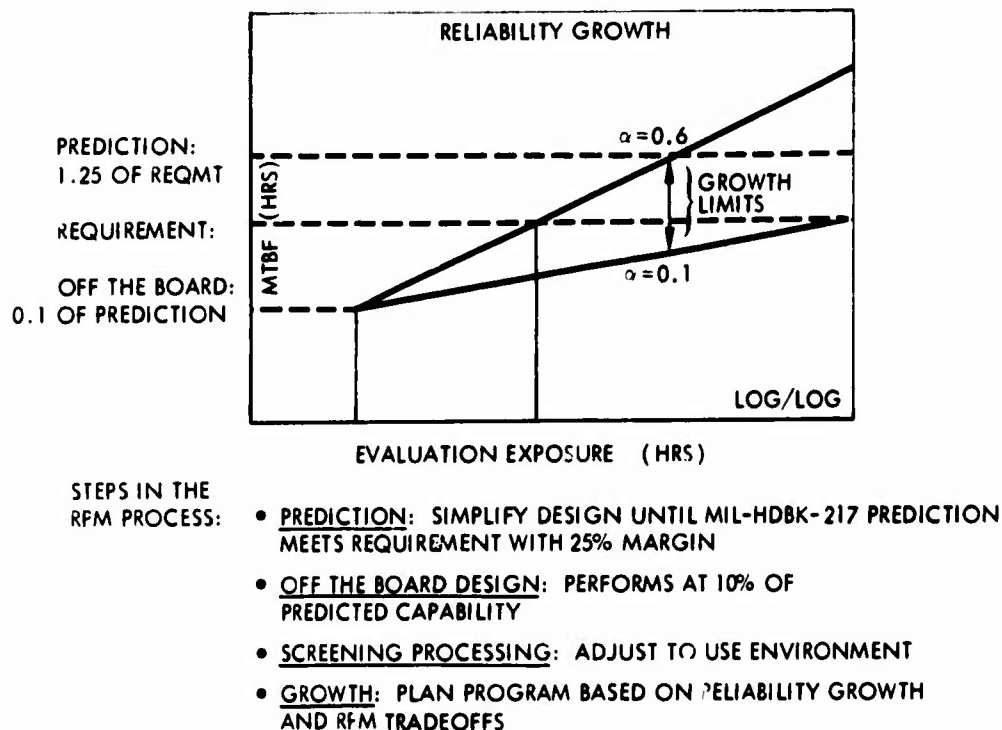


FIGURE III-16. Reliability Planning and Management (RPM)

every part, on the one hand, and the Duane test-and-fix method, on the other. The Duane test-and-fix method also requires that the source of every identifiable failure be determined and permanently eliminated. Making sure that any particular failure does not recur may entail a very substantial degree of traceability.

3. Motivation for Reliability Growth

While the Duane curves provide a methodology for management to ensure the growth of reliability, they do not necessarily provide the motivation for management to do this. One possible way of providing this motivation is to internalize life-cycle costs to the contractor, that is, to make sure that the contractor's overall profit or loss depends on the total life-cycle cost of the system. Later, in Section IV-A, on warranties, it will be seen why we believe this can be done by means of contractor maintenance warranty (CMW), that is, long-term warranty in which the contractor undertakes for a fixed price to maintain the system for a specified number of years after it is fielded.

4. Findings and Recommendations

a. Findings

- The essence of reliability is simplicity. Empirical evidence indicates clearly that most equipments of high unit production cost or high complexity have lower MTBF than equipments of lower unit production cost or lower complexity.^{39,41}
- The reliability of electronic components is improving rapidly, and design revisions to incorporate modern technology at the appropriate stage of maturity can substantially improve electronic equipment reliability without detriment to performance. However, premature or inappropriate application of new technology leads to reduced utility.⁴⁵
- Few military development programs are aimed at increasing reliability through simplification or technological upgrading while holding performance constant.⁴⁵

- Attainable reliability can be crudely predicted on the basis of equipment complexity or unit production cost. Reliability requirements in specifications, however, are not based on such predictions and thus are frequently impossibly high or needlessly low.^{39,41,45}
- System partitioning into LRUs or WRAs can be devised in a way that minimizes support costs, if this aspect of system design is considered simultaneously with planned provisioning and maintenance practices.⁴⁰
- The growth of measured reliability is often sluggish in the factory. After the equipment is received by the Services, the field reliability often never achieves growth; rather, it declines. Formal reliability monitoring and management can speed reliability growth both in the factory and in the field and make the ultimate cost and outcome predictable.
- Motivating a contractor to design for minimum life-cycle cost is an important potential stimulant to reliability improvement. One approach is to make the contractor responsible for maintenance as well as production costs through the application of long-term warranties.⁴⁶

b. Recommendations

- ★★★ Limit the complexity of new subsystem or equipment designs (as measured by criteria such as unit production cost or parts count) to a level consistent with the reliability required by a mission analysis. Require evidence of compliance as a preliminary to DSARC review for electronic subsystems of major systems, and as a preliminary to sub-DSARC review for independently developed electronic subsystems.
- ★★★ Require contractually the in-plant use of a formal management methodology, such as methods using Duane-curve monitoring, to ensure reliability growth in electronic equipments

★★★ Highest priority; ★★ high priority; ★ priority.

and systems. For field-reliability enhancement, a formal reliability-growth management technique should be applied (by Service management action or contractual requirement) to selected equipments on an experimental basis.

- ★★★ Use long-term contractor maintenance warranties to motivate the contractor to design for minimum life-cycle ccst. [See the later recommendations on warranties (Section IV-A-7) for further details.]
- ★★★ Specify the reliability of electronic equipments or systems to be consistent with predictions based on their anticipated complexity (or unit production cost, as a surrogate for complexity).
- ★★★ Undertake redesign of selected equipments with the specific objective of improving reliability while holding performance constant. The selection of equipments to be redesigned should be based on expected future utility and an observed reliability substantially lower than that predictably realizable by using up-to-date, proven technology.
- Make sure that the original design of a system takes account of the need for partitioning it into WRAs or LRUs in such a way as to optimize reliability, facilitate maintenance, and minimize support costs under a broad range of likely conditions of deployment. This will require broader application and some further development of existing mathematical models, as well as persistent emphasis on the use of valid input data.

★★★ Highest priority; ★★ high priority; ★ priority.

E. DESIGN TO FACILITATE COMPETITION

Necessity never made a good bargain.

--Benjamin Franklin

The Bucy report states:

Competition occurs before program commitment and during formulation of requirements. There is less competition after program award because there is usually a single contractor and a single customer, and the competition from other programs is only indirect.... The use of competition can, in many instances, be a more effective incentive than profit alone.... Commercial practice demonstrates that a beneficial impact on design-to-cost is made if competition is extended over the program's life. ... (We recommend) that effective hardware competition be maintained over an extended period of program development and production, as long as possible, and to the extent applicable to systems, subsystems, and components.

We believe that these observations and the recommendation, which refer to military weapons systems, apply equally well to military electronics. However, electronics' place as a subsystem of weapons systems requires special procedures in order to make extended competition possible.

Despite its use in many development programs and some production programs, competition is a missing ingredient in about two-thirds of military prime contract awards, and the larger the contract, the less the likelihood of competition (Table III-33). Over three-fourths of the number and of the dollar volume of contracts over \$10 million were non-competitive in FY 1972. That this situation extends into the electronics area is indicated by the fact that, in FY 1972, 58.5 percent of the procurement data clearances at the Army Electronics Command were for noncompetitive procurements (Table III-34).

The concept of competitive development, prototyping, and "fly-off" has been pretty well accepted both by industry and Government, and need not be harped on here. But in a large part of military electronics procurement, competition ceases when the production contractor is selected.*

*Or when the development contractor is selected, if development is by a single contractor with a high probability of a large production follow on.

TABLE III-33. MILITARY PRIME CONTRACT AWARDS,
FY 1972 AND FY 1971^a

<u>Award Size, millions</u>	<u>Dollar Amount in Category, billions</u>	<u>Percentage of Award Dollars in Category</u>	<u>Price-Competitive Dollar Volume in Category</u>	<u>Noncompetitive Dollar Volume in Category</u>
<u>FY 1972</u>				
\$10 or more	\$12.644	39.2%	23.2%	76.8%
\$5 to \$10	2.765	8.6	31.8	68.1
\$2 to \$5	4.205	13.0	37.6	62.3
\$1 to \$2	2.429	7.5	39.4	60.6
\$0.5 to \$1	2.381	7.4	40.4	59.6
\$0.3 to \$0.5	1.468	4.5	40.1	59.9
\$0.2 to \$0.3	0.976	3.0	40.7	59.3
<u>\$0.1 to \$0.2</u>	<u>1.401</u>	<u>4.3</u>	<u>42.1</u>	<u>57.9</u>
\$0.1 or more	\$28.269	57.5%	31.5%	68.5%
<u>FY 1971</u>				
\$0.1 or more	\$26.022	87.6%	33.4%	66.6%

^aSource: Ref. 47.

TABLE III-34. ARMY ELECTRONICS COMMAND
PROCUREMENT DATA CLEARANCES

	<u>Competitive</u>	<u>Noncompetitive</u>
<u>FY 1972</u>		
Number of Procurement Clearances (excluding MIPRs)	148	209
Fraction of Clearances (exclud- ing MIPRs)	41.5%	58.5%
<u>FY 1971</u>		
Number of Procurement Clearances (excluding MIPRs)	148	236
Fraction of Procurement Clear- ances (excluding MIPRs)	38.5%	61.4%

The pressures of a "one-shot" competition, exacerbated in a monopsonistic economy (one buyer, many sellers), frequently leads to contracts that are unrealistically low in price.⁴⁸ Because of the tendency of the Government to aggregate procurements into large-scale, multiyear buys, to take advantage of learning curves, the potential losses to the single winning bidder by virtue of misestimating or overdiscounting future risks can be enormous. If cost pressures force the only production contractor to resort to "changes" or other claims against the Government to ensure that he will not lose money, the Government has little choice but to accede because of schedule pressures and possibly because a planned installation has been tailored to the specific equipment design. If the contractor's deliveries are late, if the equipment reliability is less than desirable, or if the performance is poor, the Government has no immediate alternative. Because the lack of competition after award to a single contractor requires rigid contractual and configuration constraints, equipment designs are essentially frozen, sometimes for a decade, despite technological development and potential design changes that, if incorporated, could reduce cost, improve performance, and increase reliability.

It may seem paradoxical to assert that enhancing competition can resolve problems, some of which have been created by competition, but we believe it can. Specifically, it appears that, by properly laying the groundwork, it may be possible to mitigate the problems of a "one-shot" competition and monopsony in military electronics procurement and to emulate to a degree the many-buyer, many-seller civilian economy. To create the effect of many buyers and many sellers, there are two useful steps:

1. Fragment into several sequential design- and price-competitive procurements buys that under current practices would have been aggregated and awarded to a single contractor.
2. Ensure that equipments of similar performance characteristics are interchangeable, to make it possible not only for the Services to accept equipments of competing designs from several suppliers, but also for an equipment supplier to sell the same item to more than one Service.

In Section III-F, on production, it will be shown that often the reductions in price obtainable through sequential competition exceed those obtainable through aggregated buys from a single supplier. The examples shown there, however, are of pure price competition and do not involve design competition. When competition in both design and price is introduced in several successive procurements of a single item, it is anticipated that suppliers will be motivated to improve and simplify internal designs, with a resultant increase in reliability as well as a reduction in cost. To encourage such improvements, configuration control procedures must admit speedy approval of internal changes that do not affect interchangeability.

To foster continuing design competition through several successive procurements, the Government could find it necessary to increase its initial development investment by supporting more than one competitive development. However, the need for added Government support of development may well be mitigated by undertaking to test, qualify, and admit to competition designs developed on their own investment by suppliers who are motivated by the opportunity to compete several times for portions of the production requirements. Moreover, the growing adoption of a policy of continuing the development competition to the point of "fly-off" and "shoot-off" means that most of the increment of development investment needed to establish production competition will have already been made.

Continuing design and price competition is obviously best suited to moderate-to-large-size programs contemplating deliveries spread over a period during which technological growth is likely. The support of a variety of deployed designs can be facilitated by field replacement of failed units and their repair at depots or contractor facilities.

There is a second kind of competition toward which design efforts can be usefully directed: that between old and new technology. Tanks, planes, ships, and missiles are long-lived platforms in which are installed electronic subsystems that rapidly obsolesce because of external technological advances.

As these installed systems age technologically, they may be excelled in performance and reliability by equipments of more modern design. Were the modern designs fully interchangeable with the older ones without platform modification, the weapon-system manager could be presented with a significant competitive alternative in the upgrading of his system. Without such interchangeability, the manager cannot arrange to modernize without scheduling a costly and perhaps militarily risky stand-down of the weapon system to undergo installation modification.

Again, what is required is the imposition of interface standards to ensure that new equipment is conveniently interchangeable with equipment that it may replace, without requiring platform modification.

1. Findings

- Competition is a missing ingredient in about two-thirds of military prime contract awards. Even when a program does admit development competition, there is a strong tendency for the Government to become locked into a single supplier in subsequent production. The loss of Government freedom of action permits suppliers to force prices up by various devices. The use of large-scale, multiyear buys exacerbates the risks to both the Government and its suppliers, as well as inducing design stagnation in the equipment procured.
- Competition among similar equipments designed by different suppliers and the upgrading of the electronics complement of weapons systems are both now severely inhibited by the lack of interchangeability among like equipments and the consequent high cost and enormous inconvenience of modifying installations to accommodate substitutions.⁴⁹
- In commercial airline electronics and elsewhere in the civilian economy, interface standardization and continuing design and price competition are used to hold prices down, maintain alternative sources of supply, encourage design improvement, and allow for interchangeability among successive generations of electronic

subsystems. Periodic buys spaced over the procurement period minimize the impact of buyer or supplier error in any one contract.⁵⁰

2. Recommendations

★★★ Lay the groundwork for future design and price competition through production and for ready replacement of old designs by new-generation equipment by ensuring the interchangeability of similar equipments intended for similar applications. Accomplish this by including (or by requiring prime contractors to include) mechanical, electrical, and environmental interface standards for each unit as a part of military electronic equipment specifications.

Require design interchangeability when production competition or design upgrading is foreseen as desirable or likely. Equipment classes that, by virtue of large dollar volume or rapid technological growth, are judged ripe for initial application of interface standardization are: airborne communication, navigation, identification and weather radar equipments; vehicular communication equipments; and modular electronics packages for tactical missiles.

★★★ Modify approval processes for engineering-change proposals to expedite incorporation by suppliers of internal design improvements to enhance reliability and performance or inclusion of new technology to meet competition during the procurement cycle and even after deployment, if the suppliers are called upon to maintain their equipment. But keep rigid control over interface configurations to ensure interchangeability.

★★★ Obtain multiple developments of equipments conforming to interface specifications. Where the potential market for the equipment is large enough, encourage industry-financed

★★★ Highest priority; ★★ high priority; ★ priority.

development; otherwise, procure multiple developments under Government contracts.

- ★★★ Facilitate Government testing and qualification of designs offered in compliance with the specifications, whether or not the designs were developed under Government contract. Plan, prepare, and provide for retesting and requalification of modified designs submitted in production competitions subsequent to the initial competition.
- ★★★ To overcome the potential problem of spare-parts stocking and field repair of multiple equipment configurations, make use of depot repair or supplier maintenance under warranty. In the field, replace rather than repair failed replaceable units of equipment. Include warranty requirements when initiating development.
- ★★ To achieve multiple-source availability, rely on performance specifications plus environmental and interface requirements (i.e., "form-fit-function" specifications) to define equipment, rather than imposing detailed specifications on parts, processes, materials, and internal configuration.
- ★ To broaden the markets for competitive suppliers, encourage the evolution of multi-Service interface standards.

The expected benefits of these steps are:

- Pressure of competition, and expedited approval of internal configuration changes, will encourage continuous improvement⁵¹ in the capabilities of an equipment, as well as cost reduction and design simplification, throughout the equipment's procurement and possibly its deployment history.
- Interchangeability of competing equipments will provide management alternatives, should one supplier slip his delivery schedule or default.

★★★ Highest priority; ★★ high priority; ★ priority.

- Provision of standard interfaces will stabilize electronics installation provisions in ships and aircraft, and will reduce the need for modification of the installation to retrofit equipment of improved design.
- Generation interchangeability among electronic equipment will reduce weapon-system managers' dependence upon on-schedule completion of development of improved electronic subsystems; existing designs in production provide a fallback to which recourse can be had without modifying the installation provisions.
- Increased inter-Service interchangeability of equipment will expand the market of equipment suppliers, as well as provide more sources for buyers in the Services.
- The continued competition will not only reduce the need for the extensive and costly reprocurement documentation currently purchased when there is only a single design and a single supplier, but will mitigate the need for Government monitoring and micro-management of the details of development and the production processes of suppliers.
- Because of the resulting smaller sizes of procurements, errors in estimating costs or schedules and premature commitments to unrealizable designs by either buyers or sellers will not be so disastrous as they are today.

F. PRODUCTION

1. Competition in the Production Phase

Arguments in favor of extending design and price competition through production have been presented in Section III-E, "Design to Facilitate Competition." Extending competition into production requires splitting what would have been, under current practices, large aggregated procurements into smaller parts, and sequentially putting these parts up for competition. Such splitting runs contrary to the often-heard assertion that "the only way" to reduce unit costs is to increase equipment quantities. There is another way, repeatedly demonstrated in the commercial world: competition. The questions remain as to whether the sort of competition suggested above would bring about real dollar savings, and whether such savings would be adequate to offset the added front-end costs of multiple, competing developments.

Examples are at hand to illustrate that splitting large production buys and sequentially submitting each segment to price competition can save considerable money.

With 85 percent learning curves (a typical figure for electronics production), the average unit price when two equal-size buys are aggregated is theoretically 85 percent of what it would have been had the buys been made separately. With four equal buys aggregated, the theoretical fraction would be 72 percent. On the other side of the coin, merely introducing competition may bring about reductions of up to 50 percent from the previous price of a product.

Table III-35 illustrates the impact of price competition on price and learning curve for seven items, five of which were electronic.⁵² The competitor's Nth unit price is seen to be markedly lower than the original-source Nth unit price (N is the number of units delivered by the original source at the time competition takes place), but his learning curve is much flatter. Even so, the cost of obtaining the first half of the units from the original source and the next half through competition averages 82 percent of the cost of buying them all from the original source. This lends credibility to the idea that fragmenting production

procurements and sustaining competition throughout production will not only not increase the Government's production costs, but will also produce substantial production cost savings that can offset the added cost of developing competitive designs.

TABLE III-35. IMPACT OF COMPETITION ON THE PRICE^a
OF SEVEN REPROCURED ITEMS^b

Item	Competitive Price of the Nth Unit as a Percentage of Original-Source Price of the Nth Unit	Original-Source Learning Curve	Competitive Learning Curve	Total Cost of N Units From A, Plus N Units From B, as a Percentage of Total Cost of 2N Units From A ^c
1	58%	70.9%	96.6%	92.4%
2	40	95.8	97.2	72.6
3	33	87.4	99.8	72.5
4	41	84.2	95.9	76.8
5 ^d	64	74.1	90.9	95.9
6	57	78.8	96.3	88.5
7 ^d	<u>52</u>	<u>95.7</u>	<u>103.8</u>	<u>76.3</u>
Average	49%	83.8%	97.2%	82.1%

^aConstant dollars.

^bSource: Ref. 52.

^cA = original source; B = successful competitor.

^dNonelectronic.

Sustaining design competition through production requires Government procurement strategies that differ from those of the traditional competitive reprocurement, which is a pure price competition for production of a single selected design. Previous losers of an initial competition must be offered inducements to continue upgrading their designs, and potential new competitors must be offered inducements to develop competing designs. The development effort required may impose substantial financial risks on the developers. To encourage such risk-taking, the Government must provide credible assurance that the risk-taker has a reasonable expectation of realizing rewards by winning future competitions. This, in turn, requires Government assurance that all qualified designs will be admitted to future competition, and, when possible, that future competitions will be held.

As an alternative or complementary strategy, the Government can encourage continuing design and price competition partly at its own expense by making its awards not on a winner-take-all basis, but by awarding fractions of each buy to a limited number (two or three) of the competitors in proportion to the merits of their designs and prices.

While it has been observed³² that a winner-take-all strategy produces maximum cost savings in first procurement (pure price) competitions, the split-award strategy has the advantage that it puts suppliers on notice that there are ensured competitive sources for future buys, and it offers them an incentive to improve designs and reduce prices. Thus, award-splitting may be the best Government strategy for long-run savings in multiple sequential procurements.

a. Findings

- Production-price competition generally reduces the cost of military electronics. The cost reductions resulting from competition often substantially exceed those realizable by extending the price-quantity projections ("learning curves") of the original suppliers.
- Aggregating requirements into a single, large, multiyear procurement not only precludes the cost reductions obtainable from competition but also makes the Government vulnerable to upward price pressures by the selected supplier and induces design stagnation.
- The potential benefit of competition in reducing production costs is larger in high-dollar-value items and large contracts than in smaller ones, but is seldom pursued because of inhibitions against incurring the additional front-end costs associated with establishing a second source.⁵³
- Production competition may be expected to cut a substantial amount, such as 20 percent, from total production costs. The potential savings are often more than adequate to completely finance a competitive development, depending on the ratio of development costs to production costs and on the period over

which planned procurements are to take place. That period is often determined by factors such as budget limits and the need for maintaining the defense industrial base rather than by optimum production scheduling; however, the high cost of accomplishing these other objectives should be reconsidered.⁵³

- Where feasible, carrying on design competition as well as price competition through production will encourage a succession of technological improvements to the product that will mitigate the pressures for drastic design changes.⁵³
- Sustaining design competition through production requires Government procurement strategies that differ from those of the traditional competition for production of a single selected design. Losers of an initial competition must be offered inducements to continue upgrading their designs, and potential new competitors must be offered inducements to develop competing designs. The development effort required may impose substantial financial risks on the developers. To encourage the taking of such risks, the Government must be able to provide credible assurance that such risk-taking has reasonable expectation of realizing rewards by winning future competitions. A concerted effort should be made to identify systems, subsystems, and components to which this approach is applicable.^{50,54}

b. Recommendations

- ★★★ Where the quantity to be bought is large enough, depart from the conventional approach of aggregating procurements into a single large buy intended to take advantage of "learning curves." Instead, fragment the procurements into sequential buys, inviting design and price competition on each buy by the several suppliers of qualified interchangeable equipments.
- ★★ The Government must assure prospective suppliers that there will be future design and price competition. One method of so

★★★ Highest priority; ★★ high priority; ★ priority.

doing is to analyze and publish future needs and a schedule of planned competitive buys.

- ★★★ The Government must provide assurance that new or improved designs will be given full consideration in future competitions if they meet the form, fit, and function requirements that ensure interchangeability with prior designs. This implies the need for inclusion of interface requirements in Government specifications.
- ★★★ The Government must offer to perform and must be prepared to perform laboratory tests and evaluations of the actual hardware prototypes offered by bidders or prospective competitors in order to qualify the designs for current and future competition.
- ★ When it is desirable and necessary to sustain competition, award fractions of each buy to two or three competitors in proportion to the merit of their respective designs and prices, rather than making the award on a winner-take-all basis.

2. Reprocurement

In previous paragraphs we have recommended techniques for maintaining hardware competition by competitive procurement of internally different but interchangeable equipment designs. There is another, traditional, method of getting competition that is used with varying degrees of success by the electronics procurement activities of three Services: second-sourcing of a single design. The purpose of this section is not to comment on the merits of second-sourcing, but to suggest the application of an incentive to improve the efficacy of the process.

Under current procurement practices, the Government attempts to reduce its dependence on a single source of supply by buying from the original supplier a costly group of items that makes it possible to reprocure equipment from another source competitively:

★★★ Highest priority; ★★ high priority; ★ priority.

- Parts lists
- Engineering drawings
- Specifications
- Special production tools and test equipment
- Methods
- Facility plans
- Material lists
- Qualified vendor lists
- Data lists.

Despite the purchase of this reprocurement package, the history of reprocurement is replete with failures such as AN/UYK-7, NTDS displays, and FADAC, although there have also been some notable successes, particularly with Army communication equipment. Failure begins when the second-source contractors find it impossible to build the equipment to the drawings and with the tools supplied, and at the same time meet the specified performance requirements. Frequently, this comes about because of subtle errors and omissions in the drawings and process specifications. The Government, having undertaken reprocurement as a technique for reducing costs, is then reluctant to relax specifications or approve cost-increase engineering design change proposals that would resolve the conflict. In consequence, the contractor either loses money and delivers or elects to default. Such cases frequently end up before the Armed Services Board of Contract Appeals, which awards for the contractor on the basis that contractual requirements were internally inconsistent,⁵⁵ and the hoped-for reduction in price vanishes.

The use of sustained competition between two or more interchangeable designs, as previously recommended, would eliminate the need for the Government to approach reprocurement in the current, often unsatisfactory way. But where it is necessary to stick with a single design rather than permit multiple competing interchangeable designs, the process of information transfer needs to be improved. That it can be improved is clear from

the success of profit-motivated second-sourcing within industry, of which there is a great deal.

Managers in Government and industry indicate that original developers of equipment are usually reluctant to provide all the information others would need to build that equipment. This reluctance is attributed to a dislike of encouraging competition, to the detriment of the developers' profits, in the production of equipment currently supplied solely by the developers. Thus, drawings and specifications for Government use in reprocurement may be missing or inadequate. Even when they are adequate, a second source may have difficulty interpreting them and implementing the required manufacturing processes. To encourage the transfer of information from developer to second source through the provision of good drawings and engineering assistance, it appears that the rewards for doing a good job and the penalties for doing a bad one need to be strengthened. To this end, it is appropriate that the reprocurement data package called for by the Government emphasize substance as opposed to format, and that the data be paid for in installments: a nominal initial payment when an acceptable data package is delivered, and subsequent additional payments payable only upon delivery of each acceptable equipment by a new supplier to whom the data package has been furnished.

Discussions with industrial executives indicate the potential acceptability of such an arrangement. They agree that it would provide an incentive to them to offer assistance to follow-on sources, and that receipt of payments based on items successfully delivered by these sources can provide a substantial return on the effort required. They have some doubts about the strength of the incentive in areas where they have heretofore held a virtual technical monopoly, and they also question whether follow-on sources would accept proffered technical assistance.

a. Finding

- Where a single design must be procured and later reprocured, experience has shown that dependence upon reprocurement data packages to enable a second source to reproduce the design has often resulted in failure because the original reprocurement

data package cannot convey all the information required for successful production of the design. On the other hand, there is abundant commercial experience with successful licensing and second-sourcing, which occurs when the original vendor believes that having an effective second source is essential to his own profitability. In such cases, the vendor conveys the information not just via a data package but also via actual people-to-people contact.

b. Recommendation

- ★★ In selected development contracts where subsequent competitive reprocurement is anticipated, the Government should provide a payment to the developer for each accepted unit produced under Government contract from the developer's design by a supplier other than the developer. This payment should constitute a deferred part of the compensation for the reprocurement data package. Such a contracting procedure should be used by the Government on a trial basis.

★★★ Highest priority; ★★ high priority; ★ priority.

G. MAINTENANCE

Maintenance is recognized as a significant portion of the life-cycle cost of electronics. As complexity increases and as manpower becomes more expensive, maintenance will assume even greater importance. Accordingly, this study spent considerable effort exploring alternative methods of reducing the cost of electronics maintenance.

In this section, an attempt has been made to summarize the maintenance philosophies and practices of the Services as they apply to electronics. Additionally, the directives that relate to maintenance policies are discussed. With this as background, several possible areas for cost reduction are examined.

The thesis is developed that fostering competition among sources of maintenance, particularly depot maintenance, might result in significant cost reduction.

With respect to field maintenance, several approaches are explored. It seems apparent that the present trend toward shifting field maintenance back to the depots, when possible, will be salutary, although it must be done in the overall logistics context. The problem of high turnover among enlisted personnel is examined along with the attendant high cost per man-year of actual work brought on by the recent pay increases and by the expensive training approaches followed by each of the Services. The possibility of better utilization of first-term enlistees through changes in training and through the use of better job performance aids is discussed. Finally, a number of recommendations are made for reducing maintenance cost.

1. Electronic Equipment Maintenance in the Services and Factors in Maintenance Policy

a. Army electronic equipment maintenance.⁵⁶ AR 750-1 is the principal document prescribing Army equipment maintenance concepts and policies. This regulation identifies two basic activities within the equipment maintenance function: maintenance engineering and maintenance operations. Maintenance engineering involves development of maintenance support concepts, prescription of required maintenance operations, design

of maintenance support structures for end items, preparation of technical guidance, and analysis of operating experience. Maintenance operations encompass the physical performance of tasks such as inspection, servicing, adjustment, alignment, repair, overhaul, rebuilding, and modification of equipment.

Army maintenance operations are divided into five echelons. Echelons 1 and 2 are at the organization level and are concerned with minimal preventive maintenance and checkout, simple diagnosis, and remove and replace operations. Echelon 3, direct support, is performed by units assigned to installation, division, or major commanders. Direct support units (DSUs) exchange parts with the using organization, repair items requiring simple tools and equipment, and provide technical support to users. At Echelon 4, general support units (GSUs) do more complicated repairs that do not require restoration to original manufacturer tolerances or standards. The above levels are sometimes characterized as "direct" maintenance. Depot maintenance (Echelon 5) is considered "indirect" maintenance and is performed by industrial-type activities operated by the Army (organic depots) or on contract with commercial firms.

On a given item of equipment, it is the responsibility of the maintenance engineering activities within the Army Materiel Command (AMC) to determine the exact maintenance functions to be performed at the various echelons discussed above. These are prescribed on maintenance allocation charts (MACs), which are developed as part of the maintenance support planning process.

Organizational maintenance is performed almost exclusively by Army enlisted personnel. In the DSUs and GSUs, U.S. civilians and foreign nationals may be employed to augment the basic capability provided by military personnel.

Practically all organic depot maintenance in the CONUS is performed by U.S. Civil Service employees; in overseas areas the bulk of the employees in depot maintenance are civilian foreign nationals. The facilities overseas are either U.S. Government owned and operated or U.S. Government owned or leased and contractor operated.

Long-range workload programming procedures are not employed in Army maintenance echelons below the depot level. Manpower is authorized in these units on the basis of the number and type of organizations to be supported and experience with past workloads. In the depots, however, the Army uses comprehensive workload programming procedures to reconcile workload and manpower requirements and the funds available. The administration of most of the electronics depot maintenance programming procedures is a responsibility of the Army Electronics Command (AECOM), Ft. Monmouth, New Jersey, a major subordinate command of the Army Materiel Command. AECOM has centralized commodity management responsibility for virtually all electronics except electronics for missile systems.

Although the electronics-oriented depots do not report directly to AECOM, that command, through its inventory control and maintenance staff activities, develops workload programs for the CONUS depots and maintains information on workload accomplishment. AECOM also coordinates on electronics depot maintenance work performed overseas.

Practically all maintenance on missile guidance systems and components is performed in CONUS Army depots or on contract. The Army Missile Command (AMICOM), Huntsville, Alabama, also an AMC major subordinate command, performs functions related to this equipment comparable to those performed by AECOM for the remainder of Army electronic equipment. The missile maintenance work is accomplished at the Letterkenny, Anniston, Pueblo, and Red River Army depots.

With the exception of maintenance on missile guidance systems and components, Army electronics depot maintenance in the CONUS is performed at three depots: Tobyhanna Army Depot, Tobyhanna, Pennsylvania; Lexington-Blue Grass Army Depot, Lexington, Kentucky; and Sacramento Army Depot, Sacramento, California.

There is a very limited use of private commercial contract capabilities to perform maintenance functions below the depot level. The thrust of Army policy for these echelons is that contract maintenance should be employed (1) to handle workloads that temporarily exceed the capacities of the organic facilities and (2) when the work is so complex that it

requires technical qualifications generally available only from a contractor. Within the Army, small contracts are let by field commanders to meet requirements under the criteria set forth above.

The Army has chosen to place on contract only a relatively small amount--7 percent--of its depot maintenance work on electronic equipment.

b. Navy electronic equipment maintenance.⁵⁶ NAVMATINST 4790.19 is the principal document prescribing Navy electronic equipment maintenance concepts and policies. Navy maintenance operations are divided into three categories--organizational, intermediate, and depot maintenance--in contrast to the Army's five echelons.

On a given item of equipment, it is the responsibility of the maintenance engineering activities within the cognizant Navy systems commands* comprised in the Naval Material Command (NMC) to determine the exact maintenance functions to be performed on their electronic equipment at the various echelons. These are prescribed in Source Maintenance and Recoverability Standards (SMRSs) that are developed as a result of maintenance engineering analysis in conjunction with the maintenance support planning process. The SMRSs identify each repair task by echelon and prescribe standards for repair. These standards include such elements as methods and practices to be used, tolerances authorized, and wear limits.

Each Navy ship's company should possess the capability to maintain the ship's equipment at the first echelon. Larger ships such as aircraft carriers and guided-missile frigates have intermediate maintenance units aboard. In addition, intermediate maintenance repair ships and land-based units are assigned to the Atlantic and Pacific Fleets (LANTFLT and PACFLT).

Organizational maintenance is performed exclusively by Navy enlisted personnel; intermediate maintenance by Navy enlisted personnel, U.S. civilians, and foreign nationals. Organic depot maintenance is performed almost exclusively by U.S. Civil Service employees.

*There are four hardware-oriented systems commands: Naval Air Systems Command (NAVAIR), Naval Ship Systems Command (NAVSHIPS), Naval Ordnance Systems Command (NAVORD), and Naval Electronic Systems Command (NAVELEX).

The management of Navy electronic equipment maintenance is highly decentralized. Each of the four hardware-oriented systems commands within the NMC is responsible for the design, development, procurement, materiel management, maintenance engineering, refit/restoration, alteration, and modification/modernization of its assigned electronic equipment.

Once a ship has been built and NAVORD and NAVELEX equipment installed on a NAVSHIPS hull or platform along with NAVSHIPS electronic equipment, the ship becomes the responsibility of a type commander (TYCOM) in the Atlantic or Pacific Fleet. The TYCOMs, in conjunction with NAVSHIPS, which manages the shipyards (Navy depots) are responsible for the programming, workloading, and financing of the ship depot maintenance program.

NAVORD, NAVELEX, and NAVSHIPS participate in the programming, workloading, and financing of the ship depot maintenance program to the extent that they have modernization/alteration programs for electronic equipment assigned to them. The TYCOMs establish strategic priorities and make the final decisions on which modernization/alteration programs will be accomplished when their ships go in for overhaul and repair. Each shipyard maintains a sophisticated electronics maintenance capability for equipment on its assigned classes of ships. In addition to supporting the TYCOMs, the shipyards also perform electronics depot maintenance to support NAVORD, NAVELEX, and NAVSHIPS electronic equipment refit and restoration programs.

NAVAIR differs from NAVORD, NAVELEX, and NAVSHIPS in that it is directly responsible for the programming, workloading, and financing of the depot overhaul, repair, refit, and restoration programs for aircraft and their support systems/components.

The Aviation Supply Office (ASO), the Navy aviation inventory control point for components, establishes the maintenance requirements, and NAVAIR programs, workloads, and finances the electronic component repair programs at the Naval Air Rework Facilities (NARFs) and the Naval Avionics Facility Indianapolis (NAFI).*

*Naval Avionics Facility Indianapolis (NAFI) is a specialized activity responsible for design, development, prototype production, and maintenance of airborne electronic components/avionics.

depot maintenance program for the guidance and control systems on air-to-air and air-to-ground missile systems at Naval Weapon Stations and NARFs.

As in the Army, very little maintenance below depot level is done by contractors. For the last three years, the average percentage of the total Navy electronics depot maintenance program placed on contract was 16.3 percent--ship-related electronics 11.4 percent, and aircraft-related electronics 22.9 percent.

c. Air Force electronic equipment maintenance.⁵⁶ As in the Navy, maintenance production in the Air Force is divided into three categories: organizational, intermediate, and depot maintenance. The criteria for maintenance production at each echelon are essentially the same as those of the other Services.

During the initial acquisition phase, Headquarters, Air Force Logistics Command (AFLC), in conjunction with the Air Force Systems Command (AFSC) and the user command, determines the appropriate repair level designation (echelons of maintenance) criteria.* The exact maintenance functions to be performed on equipment at each echelon are prescribed. This information is published in Air Force Technical Orders (TOs), developed as a part of the maintenance support planning process. The TOs identify standards for repair, which include such criteria as "repair and return" versus "discard after use" or "failure," methods and practices to be used, tolerances authorized, and wear limits.⁵⁷

Each Air Force wing possesses the capability to maintain its equipment at the organizational and intermediate levels.** Organization maintenance is performed almost exclusively by Air Force enlisted personnel.

*The Air Force Systems Command (AFSC) is responsible for all research and development and procurement programs for new weapon and support systems. As soon as weapon and support systems become part of the Air Force operational inventory, the Air Force Logistics Command (AFLC) assumes central supply and maintenance responsibility.

**In some cases, squadrons operating separately, such as Air Defense squadrons operating from other major command bases, will be augmented to contain an intermediate level as well as an organizational level maintenance capability.

At the intermediate maintenance level, U.S. civilians and foreign nationals may be employed to augment the core capability provided by Air Force enlisted personnel. Practically all of the organic depot maintenance is performed by U.S. Civil Service employees.

The management of depot electronic equipment maintenance is highly decentralized. Each of the five AFLC Air Materiel Areas (AMAs) is responsible for the materiel management and depot maintenance programming on its assigned electronic equipment. The AMAs workload and program the organic and inter-Service specialized repair activities (SRAs). Each organic electronic equipment SRA is workloaded to its capacity, and the remaining workload, if any, is placed on contract.

The Air Force placed on contract 34.5 percent of its electronics depot maintenance workload during FY 1973. The Air Force has taken advantage of the fact that much of the specialized test and maintenance equipment and many of the labor skills required for airborne electronics/avionics maintenance are also utilized in the civilian aircraft industry. In addition, the Air Force has a relatively large amount of electronic surveillance equipment (black boxes) and electronic countermeasure equipment maintained by the original manufacturing contractors.

d. Factors in maintenance policy. The previous sections have presented a summary of the policies and practices of the Services with respect to electronics maintenance. In order to make recommendations about cost reduction in this area it would be useful to know what present costs are. Unfortunately, as discussed in Sections III-A-1, 3, and 5, DOD budgeting and cost reporting systems make it very difficult to determine the cost of electronics support. Using a variety of assumptions, several estimates have been made, however (Appendix B). The estimates range from \$4.2 to \$6.8 billion and average \$5.4 billion. Clearly, electronics maintenance is expensive and is getting more so as military manpower costs increase since, as indicated in Table III-36, most of the maintenance force is military. What can be done to control this cost? One alternative, discussed in Section IV-A, is the use of warranties; another, the use of improved maintenance aids, is discussed later in this chapter.

TABLE III-36. DOD PERSONNEL ENGAGED
IN ELECTRONICS MAINTENANCE^a

	<u>Military</u>	<u>Civilian</u> ^b
Army	42,741	4,926
Navy	56,497	8,127
Air Force	<u>73,345</u>	<u>5,548</u>
Totals	172,583	18,591

^aSource: Ref. 58.

^bCivilians engaged in depot maintenance; the number of civilians at other levels is not known exactly but is small.

The introduction of competition as an inducement to reducing costs is an alternative that should be given serious consideration. Competition among organic sources and between organic and industrial sources does not exist in any meaningful way today. Although the use of the industrial fund concept gives the appearance of an arms-length negotiation, the fact is that alternative sources of maintenance are not generally compared and industry is resorted to only after organic depots are fully workloaded or when the equipment in question requires specialists unavailable in the depots.⁵⁸

Last year the Commission on Government Procurement called attention to the established Government policy that has historically favored contracting for goods and services rather than providing them from within the Government. OMB Circular A-76 states that the Federal Government should rely on the private sector for goods and services except when (1) the use of commercial sources would delay or disrupt an agency program, (2) direct performance is required for combat support, military training, or mobilization readiness, (3) the product or service is not available from a commercial source, (4) the product or service is available from another Government agency, or (5) procurement from a commercial source will result in higher cost to the Government.

The exception in Circular A-76 for military operations is, of course, of central relevance to the DOD. The DOD policy is that the military departments will be self-sufficient, insofar as possible, in providing organizational and intermediate (O&I) maintenance ("direct" maintenance) for combat and combat support activities. Sources for maintenance at the O&I level for other than combat and combat support activities are to be determined on the basis of (a) the need for a training/rotational base for military technical personnel, (b) the security implications involved, and (c) cost-effectiveness considerations.

The DOD policy on depot maintenance ("indirect" maintenance), as stated in DOD Directive 4151.1,⁵⁹ is based on the need to sustain a flexible maintenance base capable of rapid expansion. Organic, or in-house, capability is to be kept at a minimum consistent with the capability to meet military contingencies. The general guideline is that the organic depot maintenance capacity will be planned to accomplish no more than 70 percent of the mission-essential workload requirements with loading of facility capacity at a minimum rate of 85 percent on a 40-hour week, one-shift basis. This means that the depot could somewhat more than triple its output by going to a three-shift, seven-day week. Although the policy stresses that the organic capability will be a minimum consistent with the above, other reasons for keeping depot maintenance in house are indicated:

1. To retain or upgrade technical ability within the military Service or permit effective performance of the military mission.
2. To provide necessary experience and information on the military requirement, design specifications, performance evaluations, and the review and control of costs.
3. To develop the technical competency necessary to conduct analytical evaluations of maintenance criteria, specifications, and performance data that are necessary to ensure improved performance of military equipment.

Such criteria allow wide discretion in deciding whether an activity should be done in house or be contracted out. Considering alternative to organic maintenance is an extremely sensitive matter, because chang

may affect employment in existing Government facilities. Government employee unions are understandably concerned about this when Civil-Service-operated depots are involved.

Even if one considers all depot electronics maintenance as mission-essential, only the Air Force is meeting the 70 percent criterion of DOD Directive 4151.1. Air Force electronics maintenance is 35 percent under contract. The Army figure is 7 percent, and the Navy figure is 11 percent.

Given the condition of the DOD's cost accounting systems (Sections III-A-3 and III-A-5), it is quite difficult to obtain meaningful cost comparisons between contractor and in-house maintenance. The Army Electronics Command (AECOM) conducted studies in 1968 and 1969 to compare costs at three organic depots with the costs of two contractors.⁶⁰ These studies were somewhat inconclusive because of heavy contractor start-up costs during 1968, which required considerable extrapolation to arrive at an estimate of long-range costs. Also, the 1969 analysis was incomplete because material costs were excluded. If the studies are accepted at face value, they would suggest an 8-12 percent saving if electronics maintenance is done on contract in large volume. This probably assumes a production-line process and includes no reserve capacity retained for surges in workload.

Another effort to compare organic and contract costs was a 1972 Air University thesis analyzing maintenance of nontactical two-way radio systems at 125 Air Force bases.⁶¹ The study compared the anticipated cost of contract maintenance based on commercial rates negotiated by the Government with the hypothetical cost of organic maintenance and concluded that contract costs were higher. Although the analysis was extensive, a number of the assumptions are suspect. In determining the cost to the Government of contract maintenance, \$2.5 million was added to the contract cost of \$6.8 million to cover contract administration and management; this was 37 percent of the total contract amount. In the extreme case of a separate contract for each base, this meant that \$20,000 would be expended annually by the Government to administer a contract covering the services of an average of four technicians.

If the contract administration figure were 28 percent, intuitively still too high, the conclusion of the study would have been reversed, contract maintenance being less expensive. Aside from the validity of the assumptions, the conclusion that the Air Force should do this task in house because it would be 7 percent less expensive is contrary to OMB Circular A-76, which permits a new start in house only if it saves at least 10 percent.

Another interesting but admittedly incomplete data source is a recent Boeing proposal for MINUTEMAN II support.⁶² Boeing asserted that there could be a saving of \$539 million over a 10-year period from personnel costs alone. The proposal considered only "not military-essential" positions, using Malmstrom Air Force Base as an example. No change was suggested in Civil Service manning or in the medical area. The net reduction in personnel indicated was over 20 percent. Boeing based this reduction on three factors: deletion of military duties, work/time improvement, and decrease in supporting-services personnel. It should be noted that the specific claims made in the Boeing proposal do not call on the profit motive as a driving force. The savings due to the deletion of military duties, to a better trained and more stable work force, and to the reduction in support staff would presumably also obtain if the shift were to Civil Service instead of private contractor. Boeing estimated that a military man's time on the MINUTEMAN job was reduced from 176 hours per month to 140 hours per month because of military duties such as commander's call, parades, small-arms military events, courts-boards, and base cleanup. This is a 20 percent reduction. It should be noted that this difference is under control of the military and most of it could be eliminated in many locations by means other than the use of contractors.

Boeing assumed the average service life of working-level personnel to be 6 years for the Air Force and 12 years for Boeing. After asserting that Boeing people are not only more experienced but more broadly trained, the proposal arbitrarily assigns a 60 percent productivity to Air Force personnel and 75 percent to Boeing personnel. The proposal assumes a 10 percent loss of time (12 months over 10 years) due to on-the-job training for military personnel and 1.25 percent (1.5 months over 10 years) for

contractor personnel. Since contractor personnel would be part of the local economy and would not require housing and other services, the proposal assumes a 15 percent reduction in supporting-services personnel.

Other benefits are cited but not included in the summary figures--reduced DOD overhead, reductions in support and training bases, and cost avoidance in new-facility construction.

Recognizing the sensitivity of a system like MINUTEMAN, Boeing addressed the problem of the commander's control over the operation and attempted to demonstrate that the contractor's manager could and would be responsive to the changing requirements of the commander and his staff. With respect to work continuity, no-strike clauses could be used in labor-management agreements.

The Air Force has reportedly declined to pursue the possibility of contractor support of MINUTEMAN bases on other than economic grounds, and it is not the purpose here to challenge that decision. It is, however, important that potential cost savings be examined and that civilianization of positions not military-essential be given serious consideration.

The average cost of formal training for all enlisted skills in the Services is officially estimated to be about \$11,000. Training costs for some electronic specialties are estimated to be over \$30,000. If all costs, including the cost of on-the-job training were considered, these estimates would be 25-50 percent higher. The median length of service for technicians is less than four years, given an initial reenlistment rate of 20 percent* and a career enlistment rate of 90 percent. Thus, depending on the specialty, the annual cost attributable to training of a technician with only three years' experience is \$3000-\$10,000. Considering that the longevity of contractor personnel is greater, a cost advantage exists in this area, without considering the fact that military personnel may have military duties that reduce the effective time they are able to be actually on the job.

*Data for FY 1972 suggest that the reenlistment rate has grown to 30 percent. This may reflect one of the positive effects of voluntary military service or the depressed state of the economy, and it may be temporary.

No matter how expensive, some maintenance tasks must be performed by uniformed personnel. These personnel, on ships and overseas, generate a requirement for rotation billets in CONUS. One way to reduce the number of field maintenance personnel, both here and overseas, is to move as much maintenance as possible from the lower levels and have the work performed in depots. The Army has under way two programs, Direct Supply Support and Maintenance Support Positive, that are consistent with this objective. These programs are designed to speed up the movement of equipment components between field units and depots and to remove from the field units as many relatively complex maintenance functions as possible. Problems such as packaging and transportation are being addressed. The increased use of warranties would also help to reduce the need for skilled military electronics technicians in the field. Additionally, there have been a number of satisfactory experiences with contractor representatives in war zones.⁶³ Generally speaking, reducing the need for a uniformed maintenance man overseas, by whatever means, frees a stateside position for possible civilianization.

In addition to rotation requirements, maintaining a surge capability is an important consideration. For example, the Air Force, which operates the undergraduate pilot training wing at Vance Air Force Base almost entirely by contract at a cost per pilot trained that is less than in all other similar Air Force operations, will not consider converting such operations at other bases to contract. The reason given is that the uniformed maintenance men on these bases may suddenly be needed overseas.⁶⁴

e. Findings

- Annual DOD expenditures for electronics maintenance are estimated to approximate those for production procurement (more than \$5 billion).⁶⁵
- As indicated in prior findings, electronics maintenance cost visibility is needed before management action to reduce cost can be maximally effective. DOD cost reporting systems do not now provide this visibility.

- While there is competition in the procurement process, competition among maintenance sources is rarely used as an inducement to reducing costs. Only a small fraction (about 8 percent) of the maintenance effort is contracted, while more than 90 percent is performed by military maintenance personnel and activities.⁶⁵
- The DOD policy guideline that at least 30 percent of mission-essential depot maintenance be done on contract is not being followed in electronics by the Army and Navy. The Army contracts out about 7 percent and the Navy 16 percent. (The Air Force figure is 35 percent.)
- Because of increased pay rates and increased turnover, training, and support costs, maintenance by uniformed personnel is likely to be more expensive than maintenance by contractors or Civil Service, although the lack of good cost data masks the issue.
- The provision of maintenance billets at U.S. bases to accommodate rotation of military personnel from overseas complicates the use of civilianization as a cost-reducing technique. Such rotation billets should be carefully identified as a cost element other than maintenance so that their cost can be properly ascribed.
- The present accounting system does not allow a clear separation of true maintenance costs from costs of nonmaintenance functions performed by military personnel occupying maintenance billets. Nor does the system allow a cost comparison between military and contractor maintenance or between two different military facilities.

f. Recommendations

- ★★★ As recommended earlier, institute a cost accounting system that will afford visibility of the maintenance process and make possible realistic cost comparisons between military and industrial maintenance. Implementation in all the Services of the Uniform Depot Maintenance Cost Accounting and Production Reporting

★★★ Highest priority; ★★ high priority; ★ priority.

System (OSD Instruction 7220.29) would be an important part of such a system.

- ★★ Provide separate accounts for functions other than maintenance, such as the use of U.S. maintenance billets to facilitate the rotation of military personnel not involved in maintenance, or for personnel in training.
- ★★★ Establish alternative sources of maintenance, including the maximum feasible amount of contractor maintenance, to foster competition and resultant efficiency in the maintenance process and to ensure the proper utilization of scarce military personnel in the present zero-draft environment.
- ★★ Intensify efforts to reduce field maintenance by shifting complex tasks from the organizational and intermediate levels to the depots, taking due account of increased turn-around time and transportation problems.

2. Job Performance Aids and Maintenance

As indicated earlier, organizational and intermediate-level maintenance is and will continue to be a problem for the military. Field maintenance is expensive in terms of money and, more importantly, in terms of readiness. Using contractors and warranties may improve the situation in some cases, but for the most part the military must rely on a field maintenance force composed of enlisted personnel with a median level of experience of less than three years. While it is too early to be certain, because of the end of the draft this force may come to be made up of men of lesser educational background who meet relaxed standards on Service mental fitness examinations.

Considering that electronics maintenance men spend 20 percent of their time seeking information⁶⁶ and that the information they get is often inadequate, one area of possible improvement is technical documentation. Research sponsored by all three of the military departments indicates that better maintenance can be done if technicians use job

★★★ Highest priority; ★★ high priority; ★ priority.

performance aids (JPAs); that is, documents or devices that give precise, step-by-step instructions for each task or that otherwise present in a concise and consolidated manner all information relevant to that task. Although some of the techniques investigated appear to have the potential for greatly reducing the cost of maintenance (perhaps by 30 percent or more⁶⁷) and improving equipment availability, they have had little application outside the laboratory.

The objective of all the efforts has been to provide to the technician simple, complete, and current information in a single package, without the need for cross-referencing and retention. Fully proceduralized JPAs break up a task into easily remembered steps and present unambiguous directions using simple English and relevant illustrations. A well-designed JPA is based on a careful analysis of the task the technician actually has to do and takes into consideration the amount of training and experience he has had. While one would assume that the current maintenance documentation would do just this, it rarely does. In the process of maintenance documentation, the maintenance manual is often written before the equipment has been produced and is not based on what a technician actually must do to make repairs. More often than not, the manual is descriptive of the equipment rather than being oriented toward its optimal maintenance. In analyzing the maintenance actions required for the doppler radar systems of the C-141, the Air Force found that the isolation and repair of one malfunction required reference to 165 pages of eight documents. If no false moves were made, 41 changes in document location were required.⁶⁸

Research on JPAs has been summarized a number of times; one of the most recent summaries is in Price et al.⁶⁹ Others are in Foley⁶⁸ and in Shriver et al.⁷⁰ For the most part, these have been descriptive summaries rather than critical reviews. Rowan,⁷¹ in a study associated with Electronics-X, attempted to evaluate the quality of selected JPA research projects in order to assess the claims put forward for this general approach to maintenance documentation and for particular JPAs. Table III-37 summarizes the results of this examination.

TABLE III-37. EXPERIMENTAL COMPARISONS OF INNOVATIVE JOB PERFORMANCE AIDS WITH CONVENTIONAL DOCUMENTATION^a

Concept	Year	Equipment	Number of Subjects	Results	Remarks
FORECAST	1958	Antiaircraft Fire Control System	37	Equivalent performance	60% less training time
FORECAST	1959	Antiaircraft Fire Control System	16	40% improvement in performance. Statistical significance.	60% less training time
FORECAST	1963	LORAN	98	Three times more faults identified. Statistical significance.	Same training time
JOBTRAIN	1962	Communication Equipment	39	Equivalent performance	60% less training time
MAINTRAIN	1963	NIKE AJAX Radar	16	42% more malfunctions found in 41% less time	10% level of confidence was used
Symptom-Collection Manuals	1964	HAWK Radar	44	80% isolation of faults vs. 40%. Statistical significance.	Experimental group was higher in aptitude
NIKE-X MDS (A-VIS)	1964	Target-Tracking Radar	15	Programmed material superior to conventional. Visual-only mode 27% more effective. Programmed TM 14% more effective. Significant.	Results were a mixture of content and mode of presentation
SIMNs	1964	Radar	42	SIMNs group performed at 96%, control group at 70%	
SIMNs	1971	SRC-20 Radio	178	Low-trained group better with SIMNs; high-trained group better with conventional documentation	Study was poorly designed and executed
BFIC	1966	Electronic Modules	80	Experienced group performed in 1/5 the time and made 1/5 the errors. Statistical significance.	High and low experience and aptitude groups were matched
PINO	1968	C-141A	36	Apprentices performed nontroubleshooting tasks error free. Experienced technicians did troubleshooting in 11% less time with 1/5 errors. Statistical significance.	Only experienced technicians did troubleshooting
Fully Proceduralized Troubleshooting JPAs	1968	Maintenance Task	61	High-school students performed like experienced technicians	Dubious assumptions were made to justify performance
British Algorithm	1969	Navigation Equipment	5	Average diagnosis time fell from 90 min to 31 min.	No statistical treatment reported
Nontroubleshooting JPAs	1970	F-4J	52	Inexperienced technicians using guides performed 30% better than experienced technicians using manuals. Statistical significance.	Experienced personnel also did better with guides
Fully Proceduralized JPAs, Maintenance Dependency Charts	1971	UH-1H Helicopter	90	USAF technicians better with JPAs than TMs. Apprentices better with JPAs than experienced technicians with TMs. NDCs inferior to JPAs and TMs. VNAF experienced technicians performed equally well with all aids. Apprentices did better with JPAs, outperforming experienced technicians.	Unpublished study. No statistical significance indicated in summary. Original aids full of errors
SAFEGUARD MDS Phase Four Test	1972	Radar Return Generator	13	Technician performance not significantly different from test standards	Questionable procedure used to specify standards
Nontroubleshooting JPAs	1972	Mobile Electric Power Plant	26	Inexperienced technicians made no more errors than experienced technicians	JPAs had to be validated before test could proceed

^aSource: Ref. 71.

In addition to the studies summarized in Table III-37, a number of JPAs have been developed but not formally tested. The largest number have been procured by the Air Force for Vietnamization. JPAs have been prepared for the UH-1H, the CH-47, the C-7A, three jet engines, a refueling vehicle, and two fire trucks. JPAs for organizational, intermediate, and depot maintenance are being produced for an electronic system called SEEK POINT.

The Army has developed aids for the following systems: an armament pad for aircraft, a searchlight, a storage battery, a tank engine, a gasoline-engine water pump, and a TOW launcher.

The Naval Air Systems Command (NAVAIR) has procured fully proceduralized JPAs for four high-maintenance subsystems of LAMPS and has in process the development and test of fully proceduralized JPAs for the AQA-7 sonar system. NAVAIR has also sponsored research on JPAs that can be used by personnel of differing skill levels and that contribute to on-the-job training (OJT). Unfortunately, this research, which dealt with parts of the trouble-plagued AWG-10, was canceled just as preliminary reports were indicating favorable results.

The evidence with respect to JPAs for inexperienced technicians is convincing. For experienced personnel the evidence is more equivocal. In all the experiments and field tests, inexperienced technicians performed better with fully proceduralized JPAs than with conventional documentation. Often, particularly in troubleshooting situations, the inexperienced technicians--even those who had attended the prescribed schools--were unable to perform at all using conventional manuals. However, they were able to perform with minimal errors using the JPAs, and their time to repair approached the time experienced technicians required when the latter used either conventional or experimental documentation.

Considering the overwhelming evidence from the experiments and field tests cited above, it seems clear that nontroubleshooting, fully proceduralized JPAs should be produced and widely used. Such an action would result in significant savings in the cost of maintenance in that the Services would be able to make more effective use of the new technician

who, although he has presumably been properly trained, spends many months on the job before he performs any but the simplest tasks.⁶⁶

In addition to the benefits derived from less costly maintenance and improved equipment reliability, JPAs offer the possibility of greatly reducing training costs. In general, each of the Services follows the same approach, leading to the assignment of a man to an organizational or intermediate-level maintenance position, where he is concerned with a given system. After basic training, the individual is given an extensive course in basic electronics, with emphasis on general theory. He subsequently receives shorter training in the theory and maintenance of a particular system or systems, for a total of 30 or 40 weeks of formal training. He is then assigned to a maintenance organization, and he is supposed to be capable of productive work. It is assumed, of course, that he will get additional training through OJT. Many experienced observers indicate that in practice the system does not work this way. The new technician is unable to use the conventional manuals and must be closely supervised if he does any but the most mundane maintenance task. Since OJT is often inadequate, he learns only if he is highly motivated and works with experienced personnel who are willing and able to teach him. Given the reenlistment rate and the length of training, the cost of effective maintenance finally obtained from this process is extremely high. The research literature on JPAs and training is replete with studies indicating that even men of lower aptitude can carry out nontroubleshooting maintenance tasks with minimal training if they are furnished with properly prepared JPAs. If no change were made in formal training and personnel procedures, significant improvement would still result from providing JPAs to the newly assigned technician, if only on selected subsystems, since he would immediately be able to be productive.

Even greater economy would result if the training procedures were changed. With four to six weeks of training in the use of tools and support equipment, the average recruit using JPAs should be able to perform useful work.⁷² There would be substantial and valid objections if this were the only change made. Even though the evidence indicates that new technicians derive a good deal of job satisfaction from actually doing

productive work with JPAs, effective OJT must be provided if they are to remain motivated and to increase their effectiveness. With the exception of some of the earlier studies, JPA design has not included training objectives. A number of studies indicate that learning nevertheless does occur. Research by Post and Price⁷³ indicates that modified JPAs can be an effective OJT vehicle--one that would be relatively independent of the teaching abilities and inclinations of the personnel ordinarily charged with OJT responsibility. While training-oriented JPAs would probably be more effective than the usual OJT, additional provisions would be needed for career progression for those technicians exhibiting the talent and motivation for advancement. Such personnel, should they choose to reenlist, could be sent to school after a tour of hands-on maintenance experience, a system used by the British Navy.⁷⁴

Another problem with the current training and assignment philosophy is the difficulty and expense of cross-training. Foley⁷² points out, for example, that 34 systems are the responsibility of Air Force Specialty Code 328X4 (Avionic Inertial and Radar Navigation Systems Specialist). The formal training for this career field is 37 weeks long, with 24 additional weeks of OJT. After this training, the technician is effective only on the system for which he has received OJT. When reassigned, extensive and expensive cross-training is required before the technician is again effective. Job performance aids offer the potential for significantly reducing the cost of cross-training.

a. Cost-savings potential. Hard evidence of the cost savings possible from adopting JPAs is difficult to develop. In the F-4J study,⁷⁵ a simple mathematical model of a work center was built to explore the manpower utilization implications of introducing JPAs for nontroubleshooting tasks. Without JPAs, 71 percent of the inexperienced labor is spent observing and assisting experienced technicians. The other 29 percent cannot be accommodated by the workload. If JPAs were used, 83 percent of the inexperienced labor would be performing maintenance, and the other 17 percent would be assisting. The availability of experienced technicians for complex work would increase 52 percent, the maintenance queue would decrease by 25 percent, and the number of maintenance actions failing quality assurance would decrease by 75 percent.

In the PIMO study,⁶⁷ system effectiveness estimates were also made. It is pointed out that simply utilizing time now spent in OJT for maintenance using JPAs would decrease the time a one-term enlistee spends in training by 25 percent. The improved performance expected with JPAs could improve departure reliability by 50-65 percent and operational readiness time by 38-40 percent. If such performance measures were kept at pre-PIMO levels, a reduction in unscheduled maintenance manpower of 30-39 percent would be possible.

Should JPAs be widely adopted and formal technical training reduced, very significant savings could be made in training costs. The PIMO report states that there were in 1969 approximately 5700 aircraft mechanics assigned to flight-line maintenance of the C-141A. Assuming only 1000 new men per year due to turnover, and per-man costs of \$3500 for OJT and \$4500 for formal training, over \$7,000,000 per year could be saved in this specialty by cutting training from 28 to 4 weeks.

About one-fourth of total DOD enlisted strength is in direct maintenance. Of this force of about 600,000, more than one-fifth, or 120,000, must be replaced each year because of turnover. If the PIMO calculations are extended to this entire maintenance force, the savings would be nearly a billion dollars per year. Such an extension is probably not warranted, since JPAs are not appropriate for every maintenance task. On the other hand, this is the potential cost benefit from reducing training only and does not include the benefit from better equipment availability and fewer zero-fault removals.

If these studies are at all reasonable, the cost-benefit potential of JPAs is indeed very large, but it is obtainable only by making changes that cut across the decisionmaking structure of the Services and by making investments that do not clearly accrue to the benefit of the investing agency.

One objection to JPAs has been that they cost more than conventional documentation and that project managers faced with competing requirements resist their adoption. If the cost-savings potential of JPAs is even a small fraction of what is claimed by proponents, the initial cost should

not be an overriding factor. A budget quotation submitted to AFLC in 1971 for completion of flight-line JPAs for the C-141 was \$1.3 million with troubleshooting aids and \$800,000 without.⁷⁶ McDonnell Douglas reportedly estimated that JPAs for the F-15 would cost \$45 million versus \$35 million for conventional documentation.

Most estimates indicate the cost at 100-125 percent of conventional documentation. In at least one case, SEEK POINT, estimates of JPA cost were less than the estimates for conventional manuals.

If JPAs were widely adopted, their production costs would undoubtedly come down. Current JPA estimates from contractors accustomed to producing conventional manuals are probably inflated because of uncertainty. The industrial base for this kind of product would expand, although, fortunately, there are currently at least a half-dozen contractors who have demonstrated capability in this area.

b. Need for definitive demonstration. Considering the potential of maintenance aids for less expensive maintenance, better availability of equipment, and better use of manpower, and recognizing that human-factors R&D money is very limited, it is difficult to understand why more money has not been spent in bringing this approach to a point where a clear-cut decision as to its merit could be made. The PIMO project cost \$2.8 million. All of the AFHRL effort on JPAs since 1960 cost a total of \$540,000. The early Army HumRRO work on JPAs is estimated to have cost less than \$1 million. The Navy expenditures on research in the area are about \$500,000 to date. Thus, approximately \$5 million has been spent in developing and evaluating something that shows promise of saving many times that amount annually.

Achieving efficient cost-effective maintenance is a system problem involving management procedures, procurement methods, maintenance philosophy, and training and personnel practices. The system includes a number of well-established institutions with all of the problems inherent in a complex process that has developed over a long period of time.

Perhaps the major institutional problem in getting JPAs adopted is the relation of life-cycle cost and the system acquisition process.

Inadequate weight is given to the potential cost savings in maintenance during the initial decision on what kinds of documentation to procure for the new system. Another part of the problem is on the contractor side of the documentation community. Traditional documentation is understood; it is easier to estimate and produce. Given the low priority and status that documentation activities have inside the major weapon-system firms, it is not surprising that there is little pressure for change. It seems evident that the impetus for change will only come from those having broad enough responsibility to be concerned with the whole life-cycle process.

The numerous small research studies over the years have not had the influence that maintenance-aid proponents have hoped for. Because of the general difficulties surrounding human-factors field research and the small sizes of the samples found in the maintenance-aid studies, a number of doubts remain, particularly in the troubleshooting area. There are differences of opinion, even among maintenance-aid proponents, about the optimal way to present maintenance data, and a number of issues need more study. Some of these issues have been discussed in this report.

To settle these issues and to gain the requisite broad institutional acceptance, a large-scale series of well-planned field demonstrations of JPAs should be made with the active involvement of all parties concerned with maintenance documentation. These should be funded well enough to ensure that the results will be logically compelling and, if positive, will lead to acceptance and implementation.

The Air Force Human Resources Laboratory has proposed in Project INNOVATE (Project 1194 of Program Element 63102F) an effort that, with some modification, would serve part of this purpose. This project, which has not been funded, would compare conventional technical orders, SIMMs or MDC-type decision aids, and fully proceduralized JPAs and would provide answers to the questions of whether brief technical training is adequate with JPAs and whether JPAs alleviate the cross-training problem within a specialty. It would also compare the performance of personnel of differing aptitude levels.

It is hoped that this scale of effort will also be carried out in the Army. The planned Army program to develop and demonstrate information presentation methods tailored to various commodity groups will provide additional focus on the documentation problem. Reactivation of the previously mentioned Navy work involving the AWG-10 (ADO W43-13X) would also contribute to progress in this area.

c. Findings

- There is high turnover among electronics maintenance personnel. The training period is long, and personnel seldom become productive until the end of the initial enlistment period. The median level of experience is less than three years. These factors result in an expensive and unproductive maintenance force, high training cost (averaging \$3000-\$10,000 per man-year), and high turnover.⁷⁷
- A training sequence in which a trainee first learns to perform maintenance tasks on specific equipments and defers learning general theory gives him early capability to do productive work and prepares him for later advanced study. This training sequence is the reverse of the current process.
- Successful, speedy, and accurate performance of maintenance tasks by green technicians can be made possible by the use of fully proceduralized job performance aids.

d. Recommendations

- ★★★ Develop fully proceduralized job performance aids for use in routine maintenance of new weapons systems and for selected tasks in high-maintenance portions of existing systems.
- ★★★ Selectively, on a trial basis, reorient the training sequence for electronics technicians so as to provide first the specific training they require to perform maintenance tasks by using proceduralized aids during their initial enlistments.

★★★ Highest priority; ★★ high priority; ★ priority.

- ★ Increase research on job performance aids and on job-oriented training to enable the utilization of personnel of lower ability levels and to enhance learning on the job. Apply the results in selected training programs.

★★★ Highest priority; ★★ high priority; ★ priority.

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IV. SPECIAL TOPICS

A. WARRANTIES

Take calculated risks. That is quite different from being rash.

--George Smith Patton, Jr.

The following points, made elsewhere in this report, need restating here:

1. The median reliability of a typical class of equipment--military avionics--is less than one-fourth that which can be attained, with determined effort, in superior military avionic equipment of equivalent production cost and complexity (Fig. II-5 and Section II-1).
2. Reliability often declines after equipment is deployed into the operational environment (Section III-D).
3. Reliability specifications are frequently not based on what is predictably attainable, and hence may be impossibly high or needlessly low (Section III-D).
4. Reliability development to meet realizable, though severe, objectives can be accomplished both before and after equipment deployment using an iterated test-and-fix process accompanied by Duane-curve monitoring of achieved reliability (Section III-D).

Past procurements have not, apparently, incorporated adequate incentives to impel the military electronics contractor to strive for the attainable reliability during equipment development, achieve it during production, and sustain it after deployment. In fact, there exist counterincentives: reliability specifications so low as to be useless

or so high as to be unrealizable (and, hence, meaningless and ignorable); rigid configuration control that inhibits salutary changes (Section IV-D); lucrative spare parts contracts that reward operational failures; and, most important, economic pressures to minimize costs of development and production regardless of the support-cost outcome.

One promising approach to providing a strong incentive for contractors to develop and sustain equipment reliability at levels that minimize life-cycle cost is the application of contractor maintenance warranties (CMWs) to transfer the maintenance burden and its attendant risk from the Government to the contractor. Such warranties would internalize to the contractor the sum of the production and the maintenance cost, and thus make his profit dependent not just on production costs, but on the major fraction of life-cycle cost.

The contractor maintenance warranty (CMW) is a warranty under which the contractor undertakes to maintain equipment for a stated number of years at no additional cost to the buyer. The warranty period is usually 3 to 5 years--a long period in comparison to both the typical MTBF of the equipment and the typical period during which equipment is warehoused before being put into service. Under some variants of this concept, the Government would have an option to renew the CMW for another period of several years upon expiration of the first warranty period.

Experience with commercial warranties shows them to be successful where there is a sufficiently large quantity of warranted units, a predictable distribution of operating environments, and an early and rapid feedback of operating experience with the units. Under these circumstances, the frequencies of failures of various kinds can be established, the mathematical expectation of loss can be determined, and speedy corrective actions can be taken in current production, where necessary to prevent serious losses. Under such conditions the warrantor can reasonably set a warranty price.¹ Many military applications of electronics meet these conditions. But, where these conditions are not fulfilled and the risk is unpredictable, either the warrantor must charge an inordinate risk premium (as in earthquake

casualty insurance) or the Government may consider agreeing to absorb unpredictable peak losses that are in excess of those the warrantor can afford.

In applying warranties, it is important to avoid the errors in past efforts to transfer risk from the Government to the contractor. We recall the total-package procurement approach under which the contractor was supposed to guarantee the sum of the development and production costs of a weapon system on the basis of a paper competition in the conceptual stage, before all the relevant technologies were adequately developed and before any prototypes had been built. The problem was that in a major system this transferred too much risk. If the risk involved was bigger than the net worth of the vendor, it did not really matter that the vendor signed a binding contract; his failure to meet his contract obligations could only lead to his bankruptcy. But, for political reasons and to preserve its industrial base, the Government has felt that it could not afford to force large vendors into bankruptcy. Thus, the idea of transferring an unlimited risk from the Government to the vendor has been proven to be unwise for large contracts.²

In the warranty of new military systems, the problems faced by the Government bear considerable similarity to the problems of the venture capitalist, who must decide how to motivate the entrepreneur whom he is planning to back financially. Here, too, the risk is great and the net worth of the entrepreneur is too small to provide a meaningful warranty. The venture capitalist will then invariably require that the entrepreneur invest a substantial share of his own net worth in the venture. While this does not provide any substantial financial security for the venture capitalist's investment, it does strongly motivate the entrepreneur to do his best for the success of the venture.

A similar approach may be taken toward warranties for new military systems. The bidder could be required to furnish a long-term contractor maintenance warranty (CMW), the bidder's liability for a loss being limited to a negotiated amount, possibly a significant fraction of the

bidder's net worth.* The proof that a loss has actually exceeded such a limit would be the responsibility of the contractor. Such an approach would

- Provide contractor maintenance under the warranty in most cases.
- Provide the contractor with strong motivation to design the equipment well to minimize its maintenance.
- Keep the warranty cost from going sky-high, since the downside risk would be limited.

The basic ingredient of the above approach is to transfer a large but not unlimited risk to the contractor. This can serve to motivate the contractor strongly, but it would keep the price of the "insurance-premium" component of the CMW from becoming too large.

While a final resolution of the problems entailed in pricing a warranty on contractor maintenance of military hardware must await further experience, some recent developments in mathematical models of logistics provide a reasonable basis for initial pricing experiments. The Army's Generalized Electronics Maintenance Model (GEMM) and the AFLC model have recently been applied to the determination of life-cycle maintenance cost as a function of a number of parameters such as MTBF. Thus, MTBF values obtained by a vendor at demonstration tests could be fed into the GEMM model to provide estimates of warranty costs³ (Table IV-1).

Since in practice the field MTBF does not usually attain the value attained in demonstration tests, the MTBF used in such calculations could be multiplied by a number somewhat larger than the factor

$$\bar{H} = \text{average (field MTBF/test MTBF),}$$

where \bar{H} represents the total past experience with the class of systems under consideration. Initially, of course, some special efforts would have to be made to assemble the necessary base to calculate \bar{H} .

*Such an approach may require some modifications of the ASPRs, since it imposes different dollar limits on the risks undertaken by different bidders on the same RFP.

Sensitivity calculations using GEMM could provide a basis for estimating the risk entailed in a given warranty price, and they could provide a guideline for the negotiators, allowing them to nudge the warranted MTBF upward. This would, of course, require an estimate of the standard deviation of \bar{H} , based upon past experience with the class of systems under consideration.

TABLE IV-1. SENSITIVITY OF THE LIFE-CYCLE SUPPORT COSTS OF RADAR SET AN/PPS-15 TO CHANGES IN MTBF

<u>Support Element</u>	<u>MTBF = 3,940 hr</u>	<u>MTBF = 1,970 hr</u>
Test Equipment	\$ 6,882	\$ 13,560
Publications	27,600	27,600
Parts Stockage	1,334,466	2,613,027
Float (Component)	228,310	228,310
Inventory	179,040	181,783
Training	4,524	8,914
Manpower (Maintenance)	270,790	533,511
Transportation	<u>89,728</u>	<u>141,962</u>
Total Life-Cycle Support Cost (LCSC)	\$2,141,340	\$3,748,667
Operational Availability (A_o)	91.7%	85.0%
Cost-Effectiveness (A_o /LCSC)	42.83	22.72

The proposed use of CMWs recognizes that most past DOD experience with warranties has not been extremely encouraging. The warranties most often used have been standard 1-year guarantees on parts, materials, and workmanship. In these the DOD has faced problems in administration, usage, coming to agreement with contractors, and ascertaining the actual warranty costs. This history will be described in further detail later in this section. The CMW being recommended here for experimental implementation has a long-term effectiveness, extending over several MTBF periods of the warranted equipment. Experience to date with the CMW will also be described later.

1. Description of Contractor Maintenance Warranty

For discussion here, a model contractor maintenance warranty has been selected from the numerous possible variants. The features of this CMW model believed essential for its successful operation are as follows:

- The product would be warranted for a certain number of operating hours or a certain number of years of elapsed time, whichever occurs first.
- If the product fails during the warranty period for any reason other than those completely beyond the control of the contractor, the contractor would repair or replace the failed unit at no additional cost to the Government.
- To control the time the contractor takes to repair failed units, the nominal repair-cycle time would be defined in the contract. An incentive might then be provided if the contractor consistently performs the repairs in less than the nominal time, and a penalty might be assessed if he consistently takes longer.
- Since one of the prime reasons for the CMW is to provide the contractor with a positive incentive to continuously improve the field reliability of his product, he would be given a relatively free hand to make "no-cost" changes to improve reliability during the life of the warranty. The traditional requirements for configuration-change approval would be modified as discussed in Section IV-D, on design evolution and configuration management.
- The length of the warranty would be designed to encompass several MTBF periods on the average. This would be done to provide sufficient data for making design changes that would indeed improve field reliability. The longer period would also be intended to make it profitable for the supplier to introduce cost-effective reliability improvements as a means of reducing the failure rate and, therefore, reducing his overall repair costs under the warranty.

- The warranty agreement would be a firm fixed-price arrangement. It is believed that other terms would tend to dilute the strong incentive/penalty feature of the warranty.
- The CMW concept would be introduced as part of the DDT&E package. This would make the warranty incentive active during the design phase to help produce the most reliable design configuration possible. However, care must be taken to avoid the problems of total-package procurement. The price of the warranty would be set at the time the production contract is let and would be based either on historical data, where they are available, or on MTBF data gathered during the OT&E phase.
- For long-term warranties, an annual renewal-at-Government-option plan with incremental funding might be used to provide warranty funds to the contractor for succeeding periods after the first year. Such a plan would be intended to eliminate the need for a large cash expenditure at the beginning of the program and to permit the continuing annual warranty expense to be paid for by OEM funds rather than production funds. To encourage the contractor to invest in reliability improvements, arrangements could be made for him to recover reliability-improvement costs if the Government did not continue the warranty for a previously specified number of years.

Prior experience (to be discussed) shows a number of steps that would have to be taken during the design phase. These are considered to be an essential part of the warranty model being described. To lessen disagreement about responsibility, it is important that there be no question of unauthorized repairs or tampering within the device. Access covers would be sealed; breakage of the seals would constitute a breach of the warranty. Effective warranty implementation would also be enhanced by an effective built-in go/no-go test coupled with an externally viewed, latching failure indicator.* The built-in test circuit may, of course, be prohibitively expensive, but latching fault indicators that are small, require little

* Once it is tripped by a momentary failure, a latching failure indicator stays tripped even if the failure is intermittent or self-correcting.

power, and are compatible with a wide range of electronic equipment are available for about \$31 each in quantities of 1000. Built-in time indicators would also facilitate warranty administration. These, too, are inexpensive, costing \$8-\$15 in large quantities. To ensure appropriate handling of warranted units by field personnel, each device would bear a prominently located decal, warning against tampering and unauthorized repair and containing packing and shipping instructions along with basic warranty information such as the date of acceptance and the number of hours warranted. It may sometimes be desirable, particularly for complex systems, to specify in the warranty the operating hours and/or elapsed time for each individual LRU. Such an arrangement could help guarantee proper spare levels. Troubleshooting and warranty administration would be simplified if the system were organized so that each functional group of circuitry is, insofar as possible, complete in one box and not spread among several boxes. This argues for planning for the warranty from the inception of the design phase.

2. Anticipated Benefits of Contractor Maintenance Warranties

Widespread use of CMWs would be expected to provide the benefits listed below:

- Equipment warranty would be expected to internalize to the supplier the maintenance portion, as well as the production portion, of the life-cycle cost. Hence, it would be expected to motivate the supplier to minimize life-cycle cost rather than production cost in order to increase overall profits. It would also be expected to provide a better fix on life-cycle cost, which would now be largely encompassed in the contract structure. This would make competition based on life-cycle cost more feasible.
- Because of the transfer of major maintenance responsibility to the supplier, warranty should reduce the need for detailed specifications on equipment design and construction (but not the need for performance specifications) and should reduce the corresponding need for inspection and test for compliance with detailed specifications.

- Equipment returns for repair under warranty would rapidly feed back to the supplier knowledge of deficiencies in the design, fabrication, and components of the equipment--knowledge the supplier currently has difficulty in acquiring because of the sluggish and nonlinear transfer function of the reporting systems of the Services.
- Supplier warranty should motivate the supplier/warrantor to reduce returns of defective equipment by making modifications during the equipment lifetime to improve reliability.
- The rigorous configuration control needed to facilitate maintenance of equipment by the Services could be relaxed if a supplier/warrantor were free to make changes in the internal design of equipment (at no cost to the Government and without its prior approval) to improve reliability or to take advantage of technological advances. Freedom from constraints on internal configuration should permit procurement of differing but interchangeable designs from more than one supplier/warrantor, provided that interface standards and environmental specifications are met, ensuring interchangeability.
- Through reliability improvements effected by the warrantor, and possibly through quicker repair turnaround, warranty would potentially increase the availability of equipment in the field.
- Warranty should reduce the cost and complexity of spare-pieces/parts stocking, special and general test equipment, and maintenance documentation.
- Warranty should reduce the overall cost of maintenance by making use of a more knowledgeable and stable work force than are military personnel, and by the introduction of competition into the maintenance arena.

Experience has been too meager so far to permit quantitative assessment of the value of these benefits; rather, it argues for experimental implementation wherever possible (this has already been undertaken⁴) and suggests the data and observations that should be sought in such trials.

3. Warranty Experience

An examination of warranty experience by the DOD and civilian organizations using equipment comparable to that used by the DOD was undertaken as part of this study. That experience is described below, in the context of the kind of warranty heretofore extant and the kind being proposed for trial. In an attempt to quantify the cost of warranties, commercial experience is examined.

a. One-Year Parts, Materials, and Workmanship Guarantees. A large quantity of minor electronic and electrical equipment has been covered by 1-year "failure-free" warranties (FFWs). However, the imposed conditions of the warranties have usually been limited to guarantee of workmanship and material. During 1970 and 1971 the Defense Electronics Supply Agency included this kind of warranty in all its procurement.

Military experience with such warranties for major, high-cost electronic equipment has been limited so far. During a 20-month period, only 25 contracts representing 5 percent of the total procurement expenditures of AECOM were under warranty.^{5,6} Similar situations have existed in both Navy and Air Force procurements. The paucity of warranty coverage was found to be a result of the problems encountered by the military in previous warranties. These problems centered on product quality, warranty administration, warranty cost, and equipment turnaround time. Neither the Services nor the GAO has been able to confirm that the warranties used motivated the contractors to improve product quality or performance. Investigations by both the GAO^{5,6} and DCAS⁷ have shown that faulty administration of warranties by the Government resulted in improper failure validation, incomplete warranty identification, improper handling of warranted items, poor depot material control, and a general lack of management of or responsibility for warranted items. A recent study by AFLC,⁸ containing a depot survey, indicated that only 22 percent of the warranted items at the depot were properly identified. The GAO surveyed the Air Materiel Area at Ogden in early 1973 and reported that only 51 percent of the warranted items were properly identified, and that 58 percent of these had passed the warranty expiration dates without repair.

The GAO also reported that many defective warranted items were repaired by field personnel or discarded without return.

b. Contractor Maintenance Warranties. The use of warranties covering more than one year and based on maintenance by the contractor has been extremely limited. In fact, only five meaningful examples were discovered during the Electronics-X Study. One of these five was an abortive attempt that did not materialize because of objections by the contractual and legal community within NAVAIR. These examples are discussed in the subsequent text, along with two examples of the use of warranties by the commercial airlines.

(1) CN-494A/2171P Two-Gyro Platform. In late 1967, Lear Siegler, Inc., entered into an agreement with the Aviation Supply Office of the Navy for the refurbishment of 800 CN-494A/2171P gyros. The refurbished gyros were delivered with a 1500-hour or 5-year warranty.

These 800 gyros were selected from a total population of about 2500 CN-494A/2171P units. The remaining 1700 gyros continued to be repaired by a combination of in-house maintenance and contract maintenance on a time-and-materials basis.

The MTBF of the total population of gyros at the beginning of this program (1967) was 400 hours. Since some of these gyros had been maintained by Lear Siegler on a commercial "time-and-materials" repair arrangement, the cost of an average repair was well known. The cost of the 1500-hour warranty was then based on this average experienced repair cost multiplied by a factor of 3.3, a factor that anticipated an improvement in MTBF to 454 hours as a result of the warranty. The existing MTBF of 400 hours would, of course, have resulted in a factor of 3.75 rather than the lower number of 3.3. Thus, under these terms, the warranty cost was 12 percent less than the Navy had been paying to get these repairs done by Lear Siegler* under the previous arrangement, and an immediate saving was realized.

*It is the belief of Markowitz at ASO that in 1967 the repair costs under the contractor maintenance arrangement at Lear Siegler (without FFW) were no higher than those at the Navy repair depot.

After nearly 5 years of experience, the actual MTBF of the 800 units under warranty had risen to 523 hours by April 1972. This represents an increase in MTBF of 31 percent during the warranty period.

Under the terms of this contract, the Navy realized an initial saving of 12 percent in repair costs over the 5-year period and, in addition, got a bonus of a 31 percent increase in reliability with a corresponding increase in aircraft availability. Needless to say, both the Navy and Lear Siegler are well pleased with the results of this arrangement and have just recently concluded an agreement to extend the warranty for another 5-year period at a lower price.

The reader will observe that the terms of this warranty provided for an anticipated average of 3.3 failures per unit during the 1500 operating hours. The object of this was to provide the information and incentive to the contractor to encourage continued reliability improvement during the life of the contract. In actual fact, the contractor did indeed make important design changes to lower his overall costs during the warranty period. These changes were of equal benefit to the Navy in terms of increased reliability and availability.

(2) AF24G-27 Gyro for Air Force F-111--Lear Siegler and USAF/ASD.⁹ This warranty contract resulted from a competition between Lear Siegler and General Electric, General Electric being the original supplier and designer of the device. The contract was let in late 1969 and provided for the procurement of 128 gyros with a warranty calling for 3000 hours of operation or 5 years, whichever came first.

The warranty price was based on an anticipated MTBF of 1494 hours and an average of two returns for repair during the warranty period. The field MFHBF for the previous supplier's gyro for a 24-month period in 1970-1971 was 426 hours. If one uses an operating-to-flight-hour figure of 1.63 (from Navy data on F-4 and A-4 gyros), this very roughly translates into an MTBF of 690 hours, as compared to the 1494 hours under warranty.

The unit price of the warranted gyro was \$6040, with the 5-year warranty priced at an additional \$2200. This translates into an annual warranty cost of 7.3 percent of the gyro procurement cost.

Answers to many of the questions raised by this contract are not available. Lear Siegler is preparing a report on an "Annual Warranty Effectiveness Study," which is expected to be available soon. Answers to questions such as those listed below are anticipated from this report:

- How does the annual repair cost of \$440 per gyro under the Lear Siegler warranty compare with the current repair costs of the unwarranted General Electric gyros?
- How does the actual field reliability of the Lear Siegler gyro compare with the earlier unwarranted General Electric units?

Lear Siegler has taken some positive measures that should improve the reliability and maintainability of the gyro as a result of the warranty pressures.

The ground rules of this procurement permitted the contractor considerable freedom to make changes within the device as long as the form, fit, and function of the complete device were unchanged. As a result, Lear Siegler made sweeping design changes within the unit in an attempt to improve reliability and maintainability. For example, James Harty of Lear Siegler states that the former design required 150 operations to remove a gyro wheel. By careful redesign, he states, this has been reduced to 12 operations.

As a result of analyzing field failure modes, changes have been made to improve the field reliability and thus reduce the rate of returns to Lear Siegler. One such change, cited by Colonel Lawrence C. Wright of ASD, involved modifications to gyros in production and repair to correct a drift problem experienced in the field.

A minor problem has developed involving gyros which were returned for repair but which tested "good" on receipt at Lear Siegler. This does not appear to be cataclysmic, however, since the rate of "good" tests to date is 12 percent (or four gyros).

Another area amenable to some corrective effort is the time consumed for repairs at Lear Siegler. Contractually, this was set at 45 days; however, the average time to date has been 92 days. This has been improving

recently, the average for a recent 6-month period being 73 days. This time is measured from receipt on the Lear Siegler dock to shipment of the repaired gyro from Lear Siegler.

(3) APN-194 Electronic Altimeter.¹⁰ Honeywell is the supplier of the APN-194 altimeter. The APN-194 is a redesign of an existing electronic altimeter in which the bulk of the change consists of replacing older technology with integrated circuitry. There was no requirement for any major performance improvements. The selling price is about \$5000 per unit.

Since this is a quite recent contract, there is no real information available at this time on the effects of the warranty on field performance.

The annual cost of the warranty was about 7 percent of the unit selling price of the APN-194, according to O. E. Hall of NAVAIR.

The warranty provides for Honeywell to make all repairs (with the usual exceptions) to any unit which fails during the first 1500 hours of operation or the first 2 years, whichever comes first. The contract further provides for a 45-day turnaround at Honeywell, with a penalty of one-half of 1 percent of the unit selling price for each day this is exceeded, up to a maximum of 25 percent of the unit cost.

(4) OMEGA Receiver--NAVAIR Procurement from Northrop.¹⁰ This warranty procurement is also very recent (early 1973), so no feedback on the performance and benefits actually accrued under the warranty are available.

The OMEGA receiver procurement, for use in the Navy P-3C aircraft, provided that Northrop would repair, at no additional cost, any receiver that failed within an initial 2-year period. In this case, there was no limit on the operating hours that could be amassed during the 2-year elapsed time.

Under the contract, 25 percent additional OMEGA receivers were provided as spares for replacement of receivers in the repair pipeline.

The complexity of the OMEGA receiver can be judged by its unit selling price, which is approximately \$18,000.

(5) SBK-11A/A24G-26 Attitude Gyro. There was an attempt to introduce a requirement for a warranty of 4000 hours or 8 years in a recent competitive procurement for the SBK-11A/A24G-26 gyro, involving General Electric and Lear Siegler as the competitors. In this case, the 8-year warranty cost would have amounted to about 50 percent of the contract price.

The contractual and legal community in NAVAIR objected to this arrangement on the following grounds:

- The arrangement would have used large amounts of production funds for maintenance activities that would otherwise have been properly funded on an annual basis from O&M funds.
- The arrangement would have constituted an insurance policy, and the Government does not buy insurance but relies on self-insurance instead.

In this case, the objections were sustained (the long warranty period had a great influence on this decision), and the requirement for warranty was deleted from the procurement.

(6) RDR-1F Bendix Airline Weather Radar. This radar is supplied to the commercial airlines with a 1000-hour or 1-year warranty included as part of the purchase price. Although Bendix would not divulge the percentage of the selling price involved in the warranty, the cost cannot be excessive since the entire system sells for only \$23,000, a very low figure when compared to the price of a similar weather radar built to military specifications.

This warranty is generally serviced by the airline customer in the airline avionics shop. The airline then bills Bendix for any repair costs during the warranty period.

When the RDR-1F was first introduced into service with American Airlines 3 or 4 years ago, the radar exhibited an air time between failures (ATBF) of 350 hours for the first 3 months. As a result of close cooperation between American Airlines and Bendix, this number had risen to an

average of 1400 hours during the eighth, ninth, and tenth months of service, and it averaged 2450 hours for the year 1972, according to AA records.

This improvement in reliability is certainly due in large measure to modifications introduced into the radar as a result of the warranty program.

It is also worthy of note that the RDR-1F has a built-in test capability coupled with a failure-warning annunciator.

(7) CAROUSEL IV Inertial Navigation System.¹¹ This system, which is manufactured by the General Motors Delco Electronics Division, is another example of reliability improvement under warranty.

The CAROUSEL IV is delivered with a 1-year warranty (regardless of operating hours). It is further warranted to have an MTBF of 1300 hours.

The CAROUSEL IV is installed on nearly all commercial 747s, and these aircraft average 8.9 flight hours per day (wheels up to wheels down). Because the inertial navigation system (INS) is turned on before takeoff and is turned off after landing, and also because of ground alignment time, the recorded INS operating time is about 1.4 times the recorded flight hours. Thus, the total expected operating hours during the 1-year warranty period are

$$8.9 \times 1.4 \times 365 = 4550 \text{ hours.}$$

This indicates that, on the average, the warranty period encompasses 3.5 MTBFs.

The CAROUSEL IV warranty has a provision requiring General Motors to provide additional spare units on loan if the MTBF is less than the warranted 1300 hours. These units can be used by the airlines to maintain aircraft availability until the 1300-hour MTBF is attained, since this figure was used by the airlines to establish their spares stocking level.

General Motors further guarantees a 7-day turnaround cycle for repaired units. If this cycle time is not met, General Motors must provide a spare unit on loan until the defective unit is returned.

Because of the unique nature of the system, most of the repairs under the warranty are done by General Motors rather than by the airlines. About

half the airlines are certified to do first-level repairs. This consists of isolating a trouble to a printed circuit card and replacing the card with another. Failed cards are returned to General Motors for repair. General Motors is billed for the repair costs at the airline shop under the warranty terms.

Three airlines do third-level repair work, which consists of repairs to failed cards. Only one airline has attempted second-level repairs, which consist of the repair of failed electromechanical subassemblies. In no case has an airline attempted the repair of gyros or accelerometers.

When the CAROUSEL IV was first introduced in 1971, the MTBF was between 400 and 500 hours. As a result of the warranty pressures, General Motors made extensive changes within the system, and the MTBF is currently in excess of the 1300 hours warranted. These modifications were accomplished at considerable expense to General Motors.

To prevent "infant mortality," each system receives an extensive burn-in at the factory before delivery to the airlines.

After the first year of warranty, maintenance is handled either by an extension of the warranty at a cost of \$9000 per installed system (spares are not charged for) per year or by factory repair on a case-by-case basis. Under the latter arrangement, the airline is charged a price listed in a standard-repair-cost catalog for each repair action.

The CAROUSEL IV has also been sold to the Air Force for use in the Airborne Command Post aircraft (EC-135J).¹² In this case, a warranty similar to that furnished the airlines was provided. General Motors agreed to do all maintenance on the system for a period of 1 year at a cost equivalent to 8.3 percent of the system's selling price of approximately \$100,000. They further warranted an MTBF of 1100 hours to be measured in the first 6 months of actual service in the aircraft. When the 6-month test period ended on 31 March 1972, the systems had demonstrated an MTBF of 2208 hours, over twice the reliability warranted. General Motors had agreed to furnish additional spares at one-half price if the MTBF warranty was not met.

4. Cost of Warranties

a. In-House Maintenance Versus Warranty Maintenance. An effort was made to compare the costs of in-house maintenance and warranty maintenance. Since comparable cost data on the two methods of maintenance could not be obtained from within the military Services,* a family of equipment was sought that the military and the commercial airlines both use extensively, and that is maintained without warranty by the military and under warranty by the airlines. Inertial navigation systems meet these criteria, and, since cost data on their maintenance were readily available from the military and the airlines, these data were used for comparison of in-house and warranty maintenance costs.

The data in Table IV-2 show that the annual maintenance cost of the two inertial navigation systems at Air Force depots ranges from 12.9 percent to 17.6 percent of the initial unit prices of the systems, while the cost of similar maintenance for the airlines under contractor warranty varies from 7.4 percent to 9.0 percent. On the average, then, for these systems the direct cost of Air Force depot maintenance is 1.8 times the total cost of the airlines for equivalent maintenance under contractor warranty. Moreover, it should be noted that the warranty costs are the total costs for the equivalent of depot maintenance, whereas the costs shown for Air Force depot maintenance are only the direct costs and exclude indirect costs.

While the operating environment is more severe for military aircraft than for airliners, average use of airliners is up to nine times greater than use of average military aircraft, depending on the type of aircraft. These two factors should tend to offset one another where annual maintenance costs are concerned.

Of course, the above data address only the depot side of the maintenance picture. However, according to Digby,¹³ depot repairs account for 83 percent of the maintenance cost of the inertial platform in the F-4D/E

*Where cost data were found on military use of warranty maintenance, comparable cost data on repairs by Service depots were unavailable.

TABLE IV-2. MAINTENANCE COSTS OF INERTIAL NAVIGATION SYSTEMS BY MILITARY DEPOT AND BY CONTRACTOR WARRANTY TO AIRLINES

Maintenance by Military Depot	Maintenance Under Contractor Warranty to Airlines
<p><u>INS for A-7D Aircraft.^a</u> Consists of ASN-90 INS and ASN-91 navigation computer. Accuracy 1-2 nmi/hr. Unit Cost of System: \$122,000 Annual Depot Direct Maintenance Cost: \$21,540 Annual Depot Direct Maintenance Cost as Percentage of System Unit Cost: <u>17.6%</u></p>	<p><u>CAROUSEL IV INS for 747, DC-10, and Other Aircraft.^b</u> Includes navigation computer. Accuracy 0.9 nmi/hr. Used by 35 airlines. Supplier/Contractor: Delco Electronics Division, General Motors Corporation. Unit Cost of System: \$100,000 Annual Cost of Maintenance Contract: \$9,000 Annual Total Cost of Depot Maintenance Under Warranty as Percentage of System Unit Cost: <u>9.0%</u></p>
<p><u>INS for F-4D/E Aircraft.^a</u> Consists of ASN-63 INS and ASN-46A navigation computer. Accuracy 2.5 nmi/hr. Unit Cost of System \$90,000 Annual Depot Direct Maintenance Cost: \$11,580 Annual Depot Direct Maintenance Cost as Percentage of System Unit Cost: <u>12.9%</u></p>	<p><u>Litton LTN-51 (Arinc 561) INS.^c</u> Includes navigation computer. Accuracy 1 nmi/hr. Unit Cost of System: \$107,000 Annual Cost of Litton Maintenance Contract: \$9,000 Annual Total Cost of Depot Maintenance Under Warranty as Percentage of System Unit Cost: <u>8.4%</u></p>
	<p><u>Collins INS-61B for DC-8-63F Aircraft.^d</u> Includes navigation computer. Accuracy 2 nmi/hr. Unit Cost of System: \$88,000 Annual Cost of Collins Maintenance Contract: \$6,500 Annual Total Cost of Depot Maintenance Under Warranty as Percentage of System Unit Cost: <u>7.4%</u></p>

^a Data source: Ref. 14.

^b Data source: Ref. 11.

^c Data source: Ref. 15.

^d Data source: Ref. 16.

and 92 percent of the maintenance cost of the inertial platform in the A-7D. The balance of the maintenance cost (17 percent and 8 percent, respectively) is accounted for by base maintenance.

b. Avionics Warranty Costs. Table IV-3 gives the annual costs of several warranties on avionic equipment. The CAROUSEL IV was also sold to the Air Force with a CMW for use in the EC-135J Airborne Command Post aircraft. In this case, the annual warranty cost was 8.3 percent of the acquisition cost of \$100,000. Again, no charge was made for spare systems; the annual warranty has recently been renewed for the third year.

TABLE IV-3. ANNUAL COSTS OF SOME AVIONICS WARRANTIES

<u>Equipment</u>	<u>Supplier</u>	<u>Use</u>	<u>Unit Acquisition Cost</u>	<u>Annual Cost of Warranty</u>	<u>Annual Cost as Percentage of Acquisition Cost</u>
AF 24G-27 Gyro for Air Force F-111 Aircraft ^a	Lear Siegler, Inc.	Military	\$ 6,040	\$ 440	7.3%
LTN-51 (Arinc 561) INS ^b	Liton Systems, Inc.	Commercial	107,000	9,000	8.4
CAROUSEL IV INS ^c	Delco Electronics Division, General Motors Corporation	Commercial	100,000	9,000	9.0
INS-61B ^d	Collins Radio Co.	Commercial	88,000	6,500	7.4
APN-194 Electronic Altimeter	Honeywell, Inc.	Military	4,900	343	7.0

^aData source: Ref. 17.

^bData source: Ref. 15.

^cData source: Ref. 11. This warranty charge is assessed only on installed systems. There is no warranty charge on spares. Since the airlines usually buy 35 percent spares, the annual cost based on all delivered units, including spares, is only 4.7 percent of acquisition cost.

^dData source: Ref. 16.

The above warranty costs are consistent with the findings of Balaban and Retterer, of Arinc Research Corporation, who found¹⁸ annual costs of commercial airline warranties to range from 4 percent to 10 percent of unit purchase price with spares included in the calculation. It should be noted, however, that the Arinc findings are largely based on informed opinion. There are little hard data available on the costs of warranties, particularly extended, reliability-oriented warranties like the CMW.

c. General Observations on Warranty Costs. The GAO studied the use of warranties--primarily the 1-year "failure-free" warranties discussed earlier--and could discover no auditable warranty costs from all contract warranties administered by the Navy Aviation Supply Office,^{5,6} the Army Electronics Command, and the Air Force Ogden Air Materiel Area.¹⁹ The Defense Contract Administration Services⁷ reported that warranty costs were rarely, if ever, itemized during contract negotiations and concluded that the Government had no accurate way to measure or estimate true warranty costs. A number of contractors have indicated that they do not explicitly price warranty service because they do not experience significant costs. This arises because the equipment is not used in the specified environment, or the returned items are either damaged by the Government, damaged during shipping, or found to be operating within specifications.

To provide a possible basis for assessing warranty costs by analogy, an attempt was made to ascertain warranty costs for commercial and consumer goods.

The cost of commercial warranties was investigated by contacting manufacturers of commercial electronic products and several airline warranty organizations. As was found for military equipment, the exact cost of the standard warranty is seldom, if ever, displayed separately in procurement documentation. Warranty personnel of Pan American World Airways stated that avionics subcontractors for the Boeing 747 aircraft quoted the cost of a 3-year "failure-free" warranty as part of the equipment cost. Attempts to break out the warranty cost during the procurement process were unsuccessful under the price competition. Pan American estimates these costs can amount to as much as 15 percent of the acquisition price per year. It should be noted that these contracts do not cover any scheduled maintenance of the equipment.

Warranty costs for consumer goods are also proprietary in nature and are contained in the product purchase price. Investigations in the area of radio and television equipment revealed that the cost of the initial contract warranty is a major pricing item representing cost tradeoffs in component cost, assembly-line quality control, and expected failure rates.

Such costs and the failure-rate basis for their calculation are tightly held, company-confidential information.

Although the CMW offers promise of many benefits, including a long-term saving in maintenance cost, it does appear to require an additional initial outlay of funds, of uncertain amount, to pay the warranty cost. This is alleviated to some extent by the annual-option approach and by the offsetting savings in the cost of initial spare parts and subassemblies, maintenance handbooks, maintenance training, and depot- and intermediate-level test equipment. These expenses do not have to be incurred as long as the contractor is responsible for maintenance, but they may be necessary later if the Government is to continue maintenance after the warranty expires. This will be discussed further in Section IV-A-5-b.

5. Operational Considerations

The following discussion is based on the limited military experience with CMWs to date and on consideration of commercial (e.g., airline) equipment operated under warranty.

a. Repair Locations. The best and most economical location for contractor repairs under warranty will vary with the type, quantity, and distribution of equipment under consideration and the type of contractor involved. Availability of the equipment as well as replacement spare requirements must be considered.

Generally, as shown in Part II, less complex hardware comprising only a single unit or several small units will inherently have much higher reliability than the more complex electronic systems and subsystems. Therefore, the percentage of these devices in the repair pipeline at any one time could be relatively low, making the spare-replacement-unit problem less severe. It follows that, assuming a reasonable spares level, the availability of units will not be a major problem. Shipping costs for equipment of this nature would also be relatively low. For this type of equipment, then, there will only be an occasional need for maintenance personnel in the field, and the warranty can be serviced by returning the boxes to the factory for repair.

If the equipment is widely dispersed and the contractor has a large amount of this and similar equipment in the field, it would probably be more desirable to have contractor-operated repair centers at several locations, as is now done by many manufacturers of electronic equipment for the consumer trade.

Complex electronic systems and subsystems would no doubt frequently require contractor maintenance personnel in the field at the intermediate level and occasionally at the operational level. Airborne fire-control radars are an example of this type of equipment. These radars have typically been unreliable in the field and have accounted for considerable maintenance effort in both the Air Force and the Navy. Newer digital designs are predicted to have an order-of-magnitude improvement in field reliability, and perhaps contractor warranties can help ensure that this will indeed come to pass. Table IV-4 gives a reliability analysis by line replaceable unit (LRU) of a new-generation digital fire-control radar. The manufacturer of this radar anticipates that two-thirds of the reliability predicted* in Table IV-4 (i.e., an MTBF of about 100 hours) will actually be achievable in the field. Since these systems generally are operated about half as much on the ground as in the air, the mean flight hours between failures (MFHBF) would then be about 67 hours. This failure rate would be high enough to require support by one or more contractor maintenance men at each location having a concentration of aircraft using the system. These maintenance men would have to be supplied with sufficient pieces, parts, and subassemblies to permit them to make many of the warranty repairs on the spot, thus reducing the Services' inventory of major spare assemblies required, while at the same time maintaining a high system-availability level.

Situations could occur in which the quantity, complexity, and failure rate of an electronic device are such as to make it desirable to have contractor repair personnel in the field, but in which the required repair activity is not enough to justify a full-time man. In this event, the

*Two prototype systems have been built and are currently under test. Reliability numbers are calculated predictions.

possibility could be considered of two or more contractors entering into a cooperative arrangement in which one of the contractors does the warranty servicing for himself and the others. This could be accomplished through a suitable subcontract arrangement.

TABLE IV-4. RELIABILITY PREDICTION BY LINE REPLACEABLE UNIT,
TYPICAL 1973 DESIGN, DIGITAL AIRBORNE INTERCEPT RADAR

<u>Line Replaceable Unit</u>	<u>Parts Count</u>	<u>MTBF^a Prediction, hours</u>
Antenna	60	3,500
Low-Voltage Power Supply	900	2,000
Transmitter	1,400	1,400
Servomechanism	620	3,200
Microwave Receiver	410	2,500
Waveguide (Microwave Shelf)	25	4,500
Stabilized Local Oscillator	300	5,800
Computer	90	1,300
Processor	300	300
System	4,105	150

^a Individual MTBF of line replaceable unit is high enough to permit realistic contractor maintenance warranty.

Such an arrangement would mean that contractor personnel would be required at the intermediate level in combat zones and on shipboard. There is prior experience with such arrangements. Contractor field service representatives served on shipboard and in field combat zones during World War II, the Korean War, and more recently during the war in Southeast Asia. Hughes Aircraft Company, for example (according to correspondence from J.B. Boehlert and R.G. Hardy), had 75 field support personnel in combat zones in Vietnam during the hostilities there. Nineteen of these people were there for over 6 years. Twelve more Hughes field support people served on shipboard at Yankee Station. Ken Hemmick, Manager of Electronics and Reconnaissance Systems Field Engineering and Support for Westinghouse, reports a similar set of statistics for that

organization. In this case, 77 men served for a total of 345 man-months in South Vietnam, and 50 men served a total of 272 man-months on shipboard at Yankee Station. Both Westinghouse and Hughes also had sizable numbers of men in other areas such as Israel, Lebanon, and Turkey (during the period of martial law in 1971-72).

These experiences suggest the feasibility of a worldwide system of contractor maintenance representatives to support warranty activities on electronic equipment. The numbers of personnel required for a large field of equipment, organizational arrangements for orderly interaction with local military maintenance organizations, and SOPs for the civilian TDY in peace and war would all have to be worked out as part of an increased reliance on CMWs of the kind being considered here.

b. Maintenance After Expiration of Warranty. During the warranty period the contractor is, of course, responsible for all aspects of maintenance of his equipment, including the provision of test equipment and spare piece-parts and subassemblies. There is no requirement during this period for detailed maintenance handbooks or maintenance training for military personnel.

Since all of the above would later be required in the absence of a continuing arrangement for contractor maintenance, some thought must be given to what action is to be taken when the warranty period expires. Several courses of action are possible:

- Provisions could be made in the initial procurement for an orderly phasing in of Government maintenance toward the end of the warranty period, including supply of the missing ingredients outlined above. This approach would, in general, appear to limit the compensatory savings that should be expected from warranties, except that the cost of reliability improvement and associated maintenance would be accounted for under the warranty during the early period of equipment introduction.
- The original contract can include provisions for extending the warranty, either by means of a priced option for the next period or by a stated obligation to negotiate an extension of the

warranty if the Government elects to do so. It would seem wise in adopting this course of action to ensure that the possibility of some arrangement suitable to the Government exists throughout the useful life of the equipment. Continuation of the warranty would be particularly useful if, in addition to the benefits of contractor maintenance, reliability growth during the next period appears to be a definite possibility.

- When the growth of field reliability reaches a plateau, any remaining benefits of contractor maintenance might still be enjoyed without the warranty provisions by negotiating a contract for continued maintenance by the contractor. This would obviate the need for procuring the handbooks, spares, and training mentioned earlier. Such arrangements can take the form of an annual package maintenance arrangement for a fixed price, or a "call" contract with payment on a time-and-materials basis. The former arrangement is no doubt preferable, since paperwork is simplified, the contractor is restrained by the fixed price to a more efficient operation, and pricing should be aided by historical data acquired during the preceding warranty period.

When a contractor maintenance contract is resorted to (in lieu of extended warranties) consideration should be given to the effect of competition for the continuing maintenance.

6. Problem Areas

In view of the limited experience to date, a number of problems or questions remain about contractor maintenance warranties.

a. Airline Versus Military Environment. It is generally agreed that the experience of the airline industry has been favorable. But how applicable to DOD is that experience? The airline operational structure is compatible with efficient warranty administration. The equipment is readily accountable, can be rapidly returned to the manufacturer, is generally well within the state of the art, and is subject to industry-wide pressure for high reliability and low maintenance cost. Most of the favorable experience--commercial and military--has been in avionics. How CMWs will work in other areas is unknown.

b. Administration of Warranties. Government experience with warranties, primarily short-term warranties, has generally been unsatisfactory, mainly because deficiencies in warranty administration have prevented the Government from achieving potential benefits. If warranties extend over several MTBFs, if no alternative repair sources are available, and if many equipments are procured under warranty, the Government must build an administrative and management structure better suited to this type of operation.

c. Comparative Costs. As in many other areas covered in this report, the difficulty of isolating DOD maintenance costs enters the warranty picture. The costs of alternatives are definitely relevant to decisions about using warranties. Total Government costs for such things as special handling and warranty administration, accommodation of contractor maintenance representatives, and costs that are deferred but not avoided have to be considered. Perhaps more difficult is determining the costs that are avoided and the benefit that occurs if readiness actually does increase.

d. Impact on Industrial Base. Widespread use of the CMW would probably make it more difficult for small contractors to compete, since they are less likely to have the resources and credible past performance to ensure their capability to follow through. Competition for major systems and subsystems usually involves large contractors who could perform more easily under the CMW. Performance bonds or contingent arrangements with third parties might help to alleviate the problem.

e. Modification Strategies. It is to the mutual benefit of the Government and the contractor that reliability improvements be made during the warranty period. Whether modification should be made when items are returned for repair, or during periodic inspection, or in the field, or under some other arrangement would depend on availability requirements, MTBF, type and impact of the modification, and other factors. This area requires careful study in each program.

f. Equipment Interface Problems. To minimize disagreements about causes of failure, it is important that equipment interface specifications

be carefully drawn up and that questions of line voltage surges, inadequate cooling, and so on, be anticipated. The Arinc report previously referred to contains examples of both airline and military warranty agreements that address these and other problems.

g. Realizing the Benefits. As mentioned above, much of the potential value of the CMW derives from costs that are avoided and from increased readiness. Active management in areas other than the administration of the warranty itself will be required to realize these benefits. For example, if maintenance handbooks, particularly for the depot level, are still procured, or if manning is not changed, the CMW may result in increased cost. This depends on policy for post-warranty maintenance, which would have to be worked out for separate programs, and fitted into a general strategy designed to capitalize on warranties if they prove useful.

7. Findings and Recommendations

a. Findings

- Long-term contractor maintenance warranties provide a technique by which both production and maintenance costs can be internalized to a single responsible organization: the supplier.
- Making the supplier-warrantor responsible for both production and long-term maintenance costs under fixed-price contracts will strongly motivate him to design equipment so as to reduce the sum of these costs, which constitute a major fraction of the life-cycle cost. But complete transfer of an unlimited maintenance risk to the contractor may be impractical, as may be seen by analogy to the Total-Package Procurement process. It is necessary to devise new ways--possibly new types of warranties--to accomplish this in a pragmatically acceptable manner.
- The limited experience with long-term contractor maintenance warranties to date suggests that they in fact motivate designs and modifications to increase reliability, and that the cost of contractor maintenance through warranties is substantially less than just the direct costs of military maintenance on comparable items.

- Short-term warranties on materials and workmanship have been extensively invoked in the past in military electronics procurements, but such warranties have been ineffectual and are not comparable to long-term contractor maintenance warranties.
- The use of long-term contractor maintenance warranties can serve as a competitive alternative to military repair of electronic equipment.²⁰
- Long-term contractor maintenance warranties have application to any military electronic equipment whose failed units can be replaced in the field and conveniently returned to the contractor for repair, or to which the contractor can have ready access for field repair.
- The costs of warranty maintenance should take into account the cost of any additional spare replacement units required, the costs of transportation for repair, and the warranty costs themselves. These costs should be compared with the costs of the spare components and the logistic system required to supply them to the field, plus the true direct and indirect costs of military maintenance.
- Post-warranty maintenance options include warranty renewal, maintenance contracts, or contractor training of military maintenance personnel. Any of these options would alleviate the need for excessively detailed data and manuals.
- Trial application of long-term contract maintenance warranties was requested of the Services by DDR&E and ASD(I&L) in a joint memorandum of 27 August 1973.

b. Recommendations

- ★★★ Extend the application of long-term contractor maintenance warranties to military electronics procurements.

★★★ Highest priority; ★★ high priority; ★ priority.

- ★★★ Make known the intention to contract for maintenance warranties on production equipment at the time development is initiated, so that the contractor will design to minimize total costs of production and warranty maintenance.
- ★★★ Establish a warranty review group within OSD to monitor results of trial applications, to determine desirable warranty contractual formats, and to refine the categories of equipments to which warranties are most applicable and for which warranties are most effective.
- ★★★ Initially apply long-term contractor maintenance warranties to equipments whose failed units can be replaced in the field and conveniently returned to the contractor's plant or base for repair, or to which the contractor can have ready access for field repair, such as: airborne communication, navigation, and identification equipment; modular radars; vehicular communication sets; complex manpack equipment such as LORAN C/D; forward-looking infrared (FLIR) systems; domestic communication, data processing, and radar installations.

★★★ Highest priority; ★★ high priority; ★ priority.

B. STANDARDIZATION AND SPECIFICATIONS²¹

Standardization is often suggested as a means by which the cost of electronic equipment may be reduced and its reliability improved. Conventionally, standardization is envisioned as a process in which only a limited number of designs of systems, equipment, modules, pieces, and parts are selected to be put into production and service, with the following expected benefits:

- Longer-run production of fewer designs should reduce unit production costs.
- Concentration of development and production engineering effort on a limited number of selected designs should lead to greater production uniformity, higher quality, and higher reliability of production items.
- Limiting the number of designs in service should keep down the number of types of repair parts to be stocked and reduce the cost of replacement inventory.
- Limiting the number of deployed designs should reduce the costs of maintenance labor and cut the training requirements for maintenance technicians.

Past examples of standardization of military electronic equipment lead to serious doubts as to whether the foregoing conventional standardization approach and objectives have merit when applied to the electronic equipment in weapons systems.

Any standardization approach that freezes on specific selected designs for a long period of time is simply not consistent with the explosive rate of advance of electronic technology and the military need for frequent design upgrading to improve equipment reliability and performance.

In subsequent sections, we shall discuss approaches to military electronics standardization that can induce cost reduction and reliability improvement without design stagnation. It will be seen that the objectives of military electronics standardization should be quite different from those conventionally assumed. The kinds and levels of equipment to

which standardization is applicable, the desirability of providing standard environments, and methods of implementing electronics standardization in the Department of Defense will be considered.

1. Equipment Standardization

Past standardization of equipment has been a kind of de facto accomplishment using the process of reprourement, sometimes over and over, of equipment identical to a previous design.

There is no question but that significant cost reductions can be achieved by this process when it is price-competitive (see Section III-F, on production). The fatal flaw in this standardization technique is that it freezes designs in a fast-moving technology. Two "triumphs" of avionics standardization by reprourement are the AN/ARC-34 UHF radio set and the AN/ARN-21 TACAN. The ARC-34 is installed in 24 types of Air Force aircraft, more types than any other UHF transceiver except the ARC-27. The ARN-21 is installed in at least eight types of aircraft, more types than any other TACAN. Yet these equipments have mean flight hours between failures of only 83 hours and 91 hours, respectively--reliabilities that are only about one-third of those to be expected from equipments of similar cost, complexity, and vintage, and less than one-tenth of what can be attained in modern designs to which intensive reliability development effort is applied.

In other words, freezing on standard designs failed to yield reliability.

Moreover, the existence of these standard designs failed to prevent the proliferation of new types: at least 15 additional types of UHF radio and eight types of TACAN have been developed and added to the inventory since the ARC-34 and ARN-21. Thus, one of the important products that conventional wisdom expects from standardization of selected designs was not met: holding down the number of designs put into inventory. The pressure for obtaining improved operational performance by taking advantage of the benefits offered by an advancing technology overcame the desire to stick with old designs for economic reasons.

Thus, the key to successful standardization of military electronic equipment is in providing an approach that is consistent with the need for continuing design upgrading and, at the same time, achieving the goals of reliability improvement and reduced cost. To accomplish this, the standardization approach should meet the following objectives:

1. Encourage design and price competition by ensuring interchangeability of competing designs.
2. Encourage periodic internal design upgrading and reliability growth by avoiding unnecessary restriction on internal design.
3. Ensure "generation interchangeability" of subsystems and equipments, so that outdated electronic subsystems and equipment can be readily replaced by new versions without modifying the vehicles within which they are installed.
4. Facilitate the evolution of electronic systems and variants of systems for differing applications by permitting interchange of system units that have differing performance characteristics.
5. Ensure interoperability of cooperative systems, such as communication, navigation, and identification equipments.

It is important to note that these objectives do not include minimizing the number of designs. Rather, the object is to encourage the simultaneous existence of several interchangeable designs of like equipment so that the user/purchaser may choose among designs and prices.

The standardization approach that meets these objectives is interface standardization at the black-box, LRU, or WRA level. Specific recommendations with regard to interface standardization and "form-fit-function" specifications were made in Section III-E, "Design to Facilitate Competition," and need not be repeated here. However, it is important to consider the kind and scope of electronic equipment and systems to which interface standardization is applicable.

A large part of military electronic equipment--about 80 percent--is installed in weapons systems--aircraft, missiles, ships, and tanks. The military utility of these weapons systems is more likely to be limited by

the obsolescence of the electronic elements that serve as sensors and control systems than by obsolescence or wearout of the vehicles themselves. Typically, the vehicles may become obsolete in 10 to 25 years, while the electronic equipment may get well behind the state of the art in 5 years.

In aircraft, about 20 percent of the dollar value of avionic gear is "standard-function" equipment--that is, communication, navigation, and identification equipment that is in common use and operates cooperatively with similar equipment in other aircraft or on the ground. Because of the massiveness of the cooperative system of which the standard-function equipment is part, the performance standards for the standard-function equipment change only very slowly. The equipment usually becomes obsolescent under pressure of advancing component and device technology rather than pressure of new-system performance demands.

The remaining 80 percent of the dollar value of avionics lies in "mission-oriented" electronics. Radars, forward-looking infrared imaging devices, fire-control and bombing systems, tactical navigators, missile systems, and tactical displays are subsystems on which the pressures for obsolescence include not only the advancing device technology but also new systems approaches coupled with operational needs. Thus, mission-oriented electronics tends to become obsolete more rapidly than standard-function gear.

Thus, a paradoxical situation exists in which, although it is clearly easier to establish interface standards for standard-function equipment because of its relatively stable configuration, the mission-oriented subsystems are more likely to require early and frequent upgrading or replacement in order to extend the useful lives of the weapons systems of which they are a part.

Examples of successful interface standardization can be found in both commercial and military systems. The most frequently referenced examples are those of airlines avionic equipment standardized by the Airlines Electronic Engineering Committee (AEEC), an organization that works under the aegis of Aeronautical Radio, Inc. After extensive discussions and negotiations with electronic equipment manufacturers and airframe contractors,

the AEEC, whose membership is drawn from the air transport industry, translates operational requirements into avionic equipment specifications.²² These specifications, published by Aeronautical Radio, Inc., and called "Arinc Characteristics," cover precisely and completely the required mechanical, electrical, and environmental interfaces for the specified equipment, together with the required equipment functions and performance. They do not specify details of internal design. Thus, they are "form-fit-function" specifications. Competing manufacturers who design to Arinc characteristics produce equipments that may differ radically in internal design, but, by reason of adherence to interface specifications, are interchangeable.

Although Arinc characteristics usually have been prepared to cover individual items of standard-function avionics, the method has been extended in Arinc Characteristic 582-2 to cover the Mark 2 Air Transport Area Navigation System (Fig. IV-1), a system equal in complexity to many military avionic systems. Thus, there exists proof that large-scale systems can be interface-standardized on a black-box, LRJ, or WRA basis.

At this point, it is useful to point out that interface standardization is an approach that can be used either in conjunction with functional specifications, as in Arinc characteristics, or in conjunction with conventional military specifications, wherein the internal processes, parts, and materials are specified in detail. Although, as discussed elsewhere in this report, use of functional specifications is recommended over the conventional detailed-specification approach, interface standardization can proceed independently and is not contingent upon adoption of this recommendation.

An outstanding example of the manner in which carefully controlled interface specifications can provide a framework for evolution of variants of a mission-critical system is the Navy's Standard Missile program. The program involved the evolution of missiles to meet different threats in a field of rapidly changing technology. It invoked standard interfaces with the platform, launchers, etc., so that the new Standard Missiles could be employed on the older TERRIER and TARTAR ships with only minor (usually

electrical) modifications required aboard ship. Intramissile interfaces were established and controlled so that new technology or new capability could be added a section at a time, and as a result new missiles representing completely new capabilities have been developed while making use of existing, available standard and proven missile sections and elements.

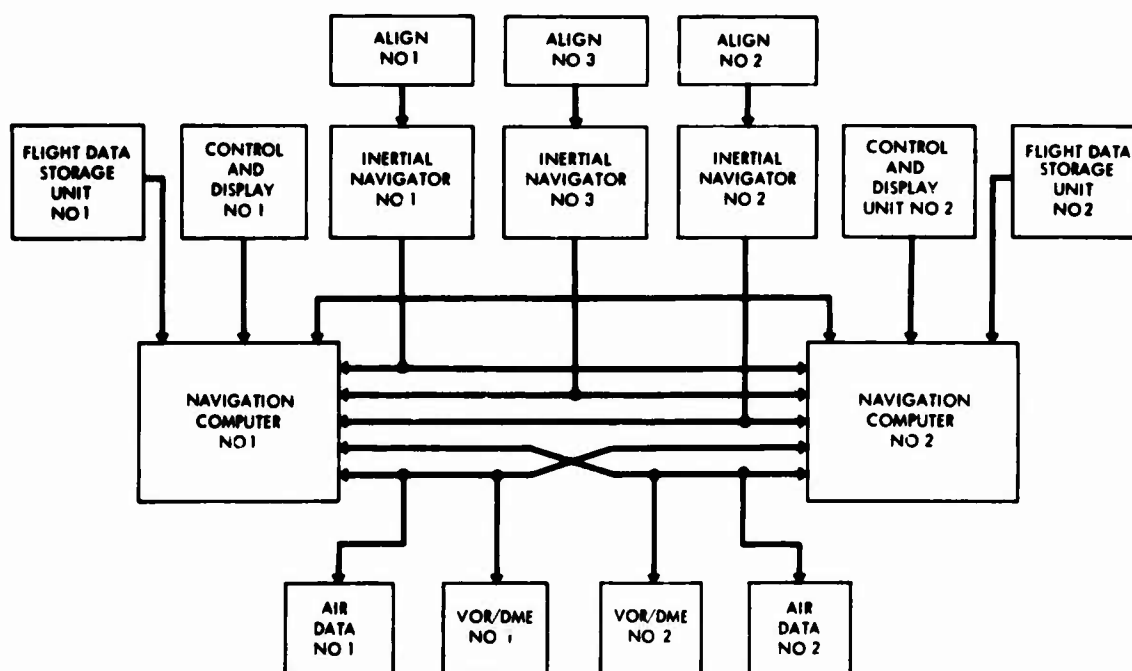


FIGURE IV-1. Complex Air Navigation System Covered by Arinc Characteristic 582-2

The sketch in Fig. IV-2 illustrates the several members of the Standard Missile (medium-range) family and the degree to which standardization has been achieved. Not shown is the fact that the Standard Missile-1 (SM-1) was itself developed by using many prior proven components, assemblies, and sections from TERRIER and TARTAR.

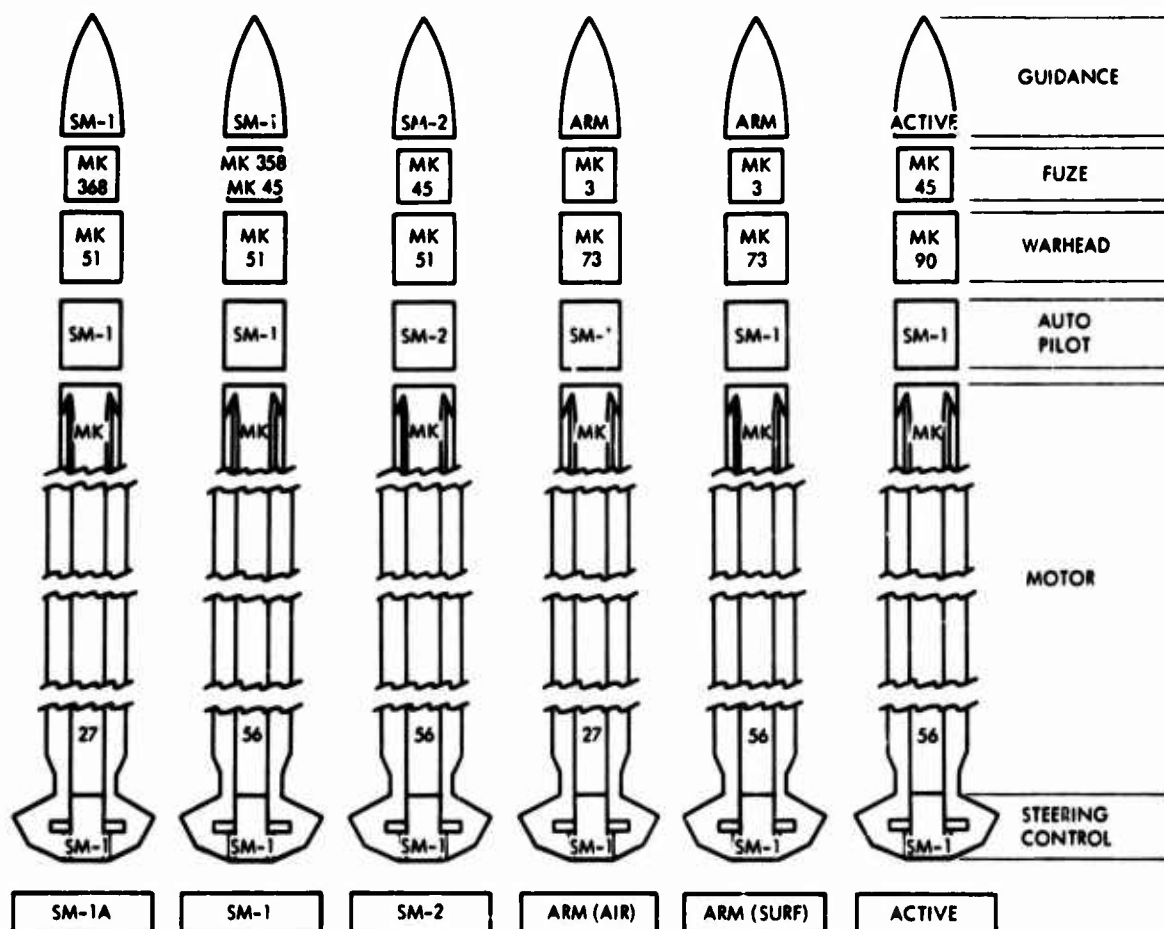


FIGURE IV-2. Medium-Range Standard Missile Family Derived from Combinations of Components

The family of medium-range Standard Missiles that has evolved now includes six surface-to-air, air-to-surface, and surface-to-surface missiles derived from various combinations of seekers (four types), fuzes (four types), warheads (three types), motors (two types), and steering control systems (one type).

The benefits of this approach can be seen in two areas. First, as shown in Fig. IV-3, the manpower in man-months and the calendar time

required to achieve the first successful guided test vehicle of each successive type have been substantially smaller than what was required for the initial Standard Missile (SM-1). Second, despite continuing performance improvement in successive missile types (e.g., doubling in altitude capability, quadrupling in range), missile production costs have stayed essentially constant.

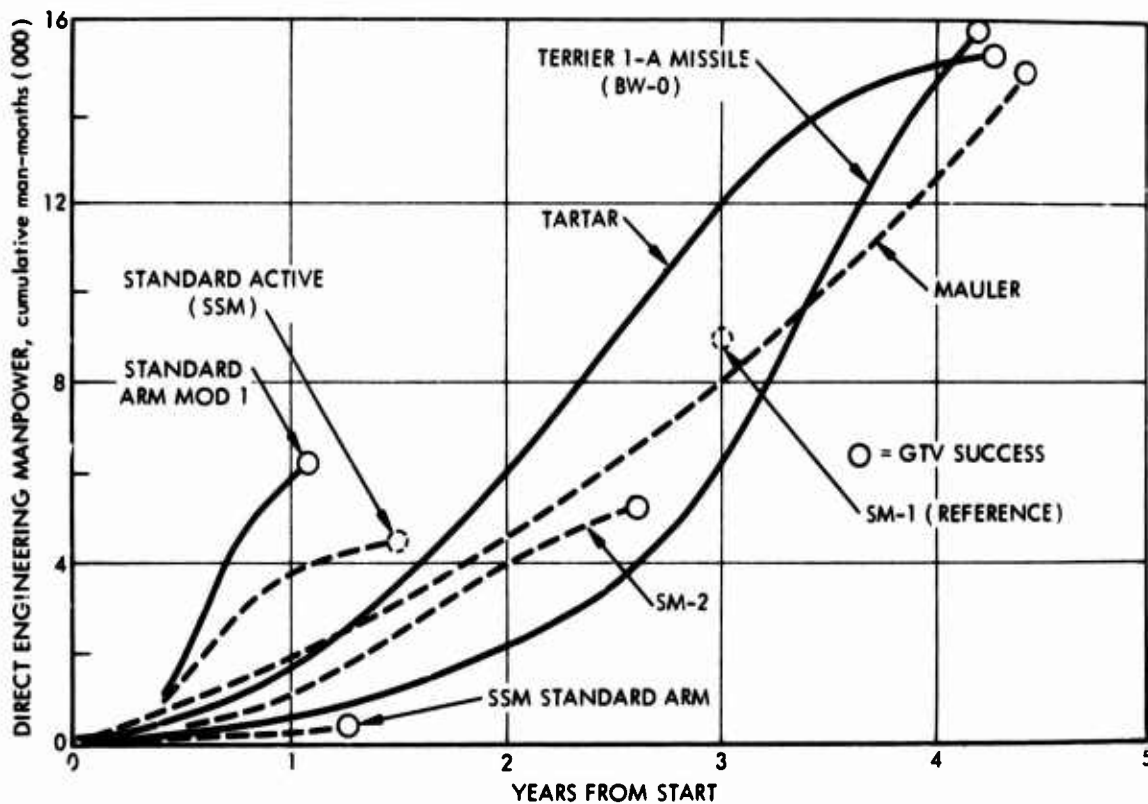


FIGURE IV-3. Manpower and Calendar Time to Achieve First Successful Guided Test Vehicle

2. Environmental Standards and Controlled Environments

Environmental design criteria for electronic equipment are imbedded in the applicable general specifications.* Characteristics of the operating environment that are specified include altitude, temperature, moisture, sand, dust, salt atmosphere, fungus, acceleration, vibration, and shock. Environmental qualification tests are covered in MIL-STD-810.

The environment is both "natural" and "induced." MIL-STD-210 is a compilation of measured natural environmental conditions throughout the world. The induced environment is primarily shock and vibration, and has been established by measuring instruments on the various platforms--people, aircraft, missiles, ships, tanks, and trucks--on which electronic equipment is to be installed. Environmental design criteria take into account the range of environments likely to be encountered by the various platforms and the degree of isolation and protection afforded the electronic equipment as installed.

Despite the decades of effort in establishing environmental design criteria, environmental failures continue to occur. In a recent study²³ of 175 aircraft in Southeast Asia over a 2-year period, it was determined that 52 percent of the avionics failures were environmentally caused. The cost of environmental failures is estimated at more than \$100,000 per aircraft per year. The distribution of environmental failure causes was as follows:

Temperature	42%
Vibration	28%
Humidity	20%
Sand and Dust	6%
Shock	2%
Altitude	2%

Elimination of these environmentally caused failures would provide benefits of \$400 million per year in a fleet of 4,000 tactical aircraft.

*There are 13 such general specifications covering the various classes and applications of electronics.

Environmental failures also occur in ship and other installations. Discussions with Air Force and Navy laboratory personnel indicate that testing in accordance with the procedures specified by MIL-STD-810 is inadequate in that it fails to expose the equipment to environmental stresses in ways that realistically emulate those operationally encountered: combinations of temperature, altitude, and humidity; temperature cycling; combinations of sand, dust, and moisture; vibration for periods of time long enough to possibly induce fatigue.

Additionally, the environmental criteria of the general specifications have inadequacies. For both ships and aircraft, the vibration, blast, and shock due to firing of one's own weapons are not adequately covered, according to laboratory experts. On ships, low-temperature requirements are overemphasized; while on aircraft, cycling of temperatures in combination with altitude and humidity is underemphasized.

Because of the desirability of diversifying the applicability of electronic equipment to many platforms of a class, rather than designing equipment that is unique to a particular platform, the approach of aggregating environmental profiles to arrive at expected environmental extremes within which equipment shall function appears to be appropriate and should be continued. There is, of course, a cost and overspecification penalty that must be paid for this form of standardization.

There is, however, another approach that requires continued design and development and serious investigation and study to determine its relative costs and benefits. That approach is the provision of a benign, protected environment in appropriate platforms--aircraft, ships, vans, and helihuts. In such circumstances, clean, moisture-free, constant-temperature air can be provided. Enclosures can be isolated from shock, vibration, and blast. The benefits of such an approach are indicated to some degree by the differences in price of commercial airlines avionic gear, which operates in a controlled environment, and avionic equipment of very similar performance characteristics (but which must operate in a more severe environment) procured by the military. Price differences of two to one (military versus commercial) are not uncommon, though part of this

difference in price must be accounted for by imposition of arbitrary "how-to" military specifications and by competition-restrictive military procurement practices.

To bring this approach into more general military usage, it will be necessary to carry out programs of measurement aimed at updating the environmental criteria of general specifications and of qualification test procedures. It will also be necessary to encourage cost-benefit analyses and development efforts related to the provision of standard, benign-environment enclosures for electronic equipment.

3. Elimination of Unnecessarily Restrictive Specifications

In an Air Force sponsored study of contract requirements shown as "Q Eagle," Lamont Brown and Paul Lee of Hughes Aircraft Company examined the hierarchies of technical specifications imposed by the military Services in development contracts. They found, for a typical electronic system of 14,000 to 100,000 electronic components, that there were 3,000 traceable specifications applicable.

These specifications are invoked through application of any of the 13 general specifications covering the various classes of electronic equipment, such as MIL-E-16400 for ship equipment, MIL-E-5400 for airborne equipment, or MIL-E-4158 for ground equipment. The general specifications themselves contain hundreds of reference specifications. In addition, they invoke MIL-Bulletin-400 and MIL-STD-454, each of which, in turn, invokes a tier of 700 to 800 specifications.

Most of the reference specifications cover parts, materials, finishes, and processes. Many are duplicative and overlapping, and in some cases conflicting. Finishes, for example, are covered in 20 different specifications. The main emphases of the reference specifications are on

- Physical rather than functional requirements
- Finish and appearance
- Fabrication practices
- Pedigree of parts and materials.

Though these reference specifications are frequently related only remotely and indirectly to the objective of realizing the desired performance of the electronic system to which they apply, they provide a ready basis for rejection by Government inspectors of equipment that is totally satisfactory from a functional standpoint. Because of the vastness of the number of applicable specifications, a potential for their selective enforcement exists that may be unfairly discriminating against or in favor of competing contractors. The costs of application and enforcement of these specifications appear to be quite large in dollars, delays, and irritation. There are very substantial administrative costs, for example, associated with ensuring material conformity with applicable specifications or obtaining waivers if conforming material is inapplicable or unavailable.

Specifications of the "how to do it" variety are described by Brown and Lee as "monuments to people who got stung." There remains, of course, the question of whether continued invocation of these specifications is essential to preclude the purchaser's being stung in the future. Comparative examples from the practices of the commercial airlines and the military indicate that the answer to that question is negative. Myron F. Wilson of Collins Radio Company points out that an airlines VHF transceiver is specified by just 10 documents, while the Air Force AN/ARC-XXX VHF transceiver invokes 456 standards and specifications (Fig. IV-4). Yet, in general, airline electronic equipment is cheaper than military equipment of equivalent type and is just as reliable.

The approach of the air transport industry relies primarily on specification of the operational performance required of electronic equipment and specification of those physical, environmental, and electrical interfaces that will ensure the interchangeability of equipments built to the same specifications. The success of the air transport industry approach appears to be based on the following factors:

- Specifications (i.e., Arinc characteristics) are the product of a mutual effort of the airline users and the electronic equipment suppliers, and hence realizability is an important implicit ingredient.

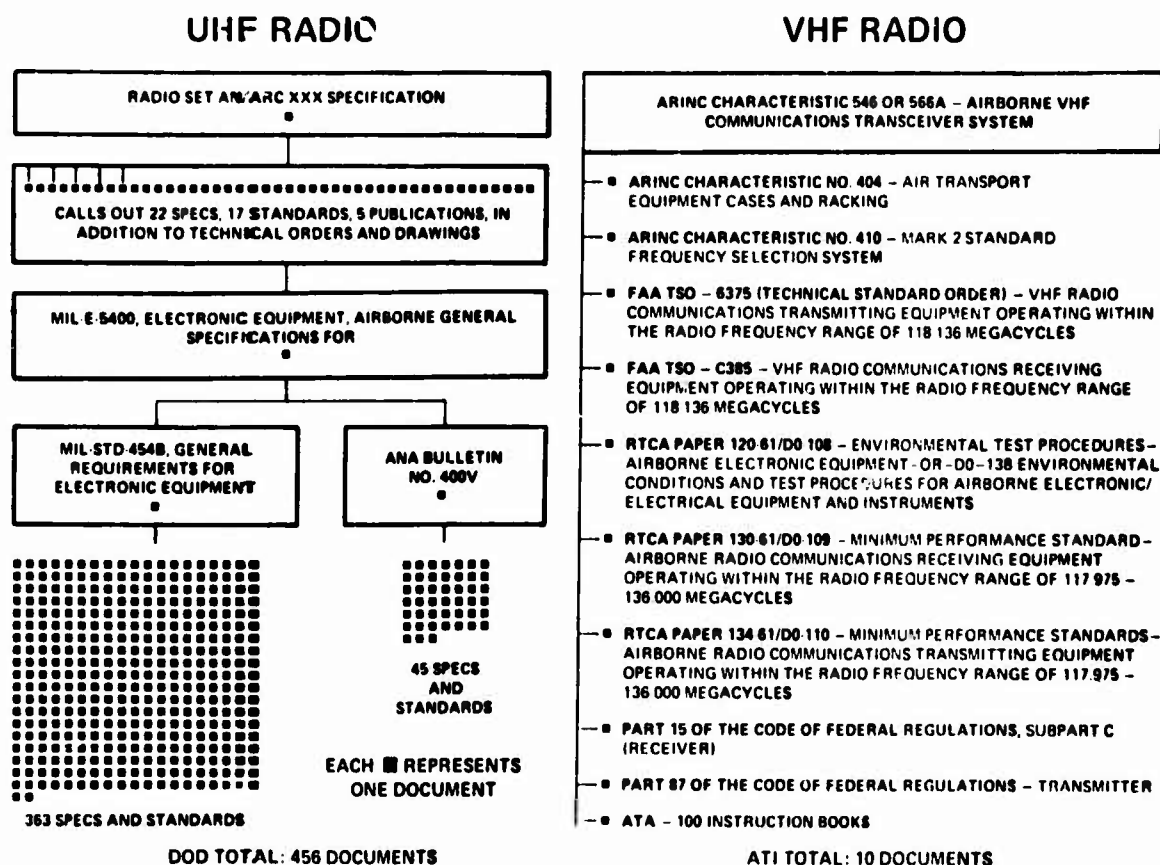


FIGURE IV-4. Comparative Specifications and Standards Requirements for Equivalent DOD and Air Transport Industry Equipment
(Source: Ref. 24)

- The widespread provision of long-term warranties (similar to the contractor maintenance warranties discussed elsewhere in this report) by equipment suppliers assures the purchaser that he will get the required functional performance despite his not specifying internal design details.
- The ensurance of interchangeability of competing equipments built to the same specification encourages continuing design and price competition between contending suppliers and promotes product improvement; and the product choices thereby available to the purchaser also mitigate the need for specification of details of internal design.

A fundamental problem of military specifications and standards for electronics fabrication practices, finishes, and processes is that the vast and rapid shifts in technology, combined with the sluggishness of the bureaucracy, almost ensure that military specifications and standards will restrict tomorrow's electronics to yesterday's practices. At the same time, the immutable military policy of admitting ingenuous novices in military electronics design and manufacture to the competition for development and production of hardware argues in favor of retaining such specifications and standards as instructive guidelines for the naive, even though those specifications and standards may be obsolescent and, to the most advanced suppliers, even irrelevant and counterproductive.

The elimination of the MIL-SPEC burden can substantially reduce the cost of electronic systems. The Swiss TARAN airborne fire-control and missile system, where MIL-SPECs were not applicable, was, according to Hughes Aircraft Company representatives, lower in cost of material than equivalent U.S. systems by 25-50 percent. According to Hughes, the equipment has performed to the complete satisfaction of the Swiss Government, and the cost to Hughes of repairs under the warranty has been negligible.

4. Electronic Standards Program Implementation

The importance, utility, and need for interface (form-fit-function) standardization at the electronic equipment, subsystem, and system level have been established earlier in this chapter and in Section III-E. The

desirability of providing standards that will permit interchangeability and interoperability of electronic equipment and systems among the Services has also been pointed out. Finally, the benefits of providing standard environments within which electronic equipment for ships, aircraft, and vehicles are to operate has been demonstrated.

The multi-Service character of the electronics standardization task and the need for broad policy changes to accomplish standardization suggest the need for an electronic standards organization within the Office of the Secretary of Defense.

Existing institutional vehicles for standardization are two. DOD Directive 4120.3, entitled "Department of Defense Standardization Programs," dated June 6, 1973, establishes policies and assigns responsibilities for the Defense Standardization Program. The implementing regulations of the Army, Navy, and Air Force substantially repeat the DOD policies. Another DOD directive, 5100.35, established the Military Communications Electronics Board and assigned as one of the Board functions the establishment of "principles and procedures for obtaining compatibility and standardization of communications-electronics systems and equipments."

It appears that DOD Directive 4120.3 can be the vehicle for the establishment of an effective electronic standards organization. To accomplish this, the Defense Materiel Specifications and Standards Board, with the concurrence of ASD(T), should, under paragraph VII B2 of the DOD Directive, recommend the establishment of an Electronic Standards Panel (ESP), with the authority and responsibility to promulgate multi-Service electronic standards and promote the cause of electronic equipment, subsystem, and system standardization, both single-Service and multi-Service. The ESP should be given the further authority to establish continuing (as opposed to ad hoc) committees, to which may be delegated segments of the authority and responsibility of the ESP.

5. Findings and Recommendations

a. Findings

- In the rapidly moving technology of military electronics, the standardization that occurs because of repeated procurements of

the same design can result in technological stagnation, mediocre reliability, and excessive proliferation of alternative equipments. This has been exemplified by the AN/ARC-34 UHF radio set and the AN/ARN-21 TACAN.

- By way of contrast, interface standardization at the black-box, LRU, or WRA level provides a practical form of standardization which has been shown to work both in the civilian airline industry and in military mission-oriented equipment, such as the Navy's Standard Missile. As used by the airline industry, the interface standardization approach is combined with functional specifications, that is, "form-fit-function" standardization. This has the advantage that while the interface is standardized, the internal configuration of the unit can evolve as technology changes, taking advantage of new devices and new materials. Interface standardization can be used in conjunction with military standards for components and workmanship. Limitations on the evolution inside the unit result, but these specifications provide a degree of insurance against the mistakes of an incompetent or greedy vendor. In either case, technological progress is not halted by standardization. Moreover, interchangeability between old and new generations of electronics becomes a practical reality, and the need for modifications to an installation to accommodate the new equipment is eliminated. With interface standardization, production costs can be held down by competition among interchangeable designs, and new systems can be synthesized largely from proven standard units.
- Strict military environmental requirements imposed on equipment and systems cause great increases in cost. The provision of more benign standard environments for electronic equipments through control of humidity and temperature and isolation from shock and vibration would make possible the use of cheaper and more readily available devices.
- In an area as dynamic as electronic technology, the vast DOD system of military standards and specifications is too sluggish

to follow the rapid advances in technology. But by providing instructive guidelines for the uninitiated, it does have the valuable function of admitting novices in military electronics design and manufacture to the competition for development and production of hardware.

- Integrated-circuit development is being driven by commercial rather than military demand, and the production prices of such items produced in commercial volume are very low. Military equipment developers should make use of the existing library of commercial MSI and LSI components where feasible, rather than entering into uniquely military integrated-circuit developments; and dependence on a single source for such components should be avoided wherever possible.²⁵
- The impact of standardization and specifications on electronics cost is of such large magnitude that establishing electronics standardization and specification policy should be undertaken in the Office of the Secretary of Defense.

b. Recommendations

*** DOD should establish an Electronic Standards Panel having responsibility and authority to

- *** 1. Promulgate policy requiring that the Services include electrical, mechanical, and environmental interface specifications in specifications for electronic equipment.
- ** 2. Promulgate policy requiring that the Services take steps toward ensuring that new electronic equipments that are likely to replace older equipments in aircraft, ground vehicles, and other platforms will be made electrically, mechanically, and environmentally interchangeable with the older equipments, of similar

*** Highest priority; ** high priority; * priority.

types, so that the new equipments can be substituted for the old without costly installation modification.

- ★★★ 3. Promulgate policy requiring that equipment, subsystems, or systems of similar types be developed to the same interface specifications, so that they may be interchanged.
- ★★ 4. Promulgate specific interface standards for classes of equipment used by more than one Service.
- ★★ 5. Establish and promulgate standards for the thermal, atmospheric, vibration, shock, mounting, shielding, and power-source environments to be provided by aircraft, ships, and vehicles in which electronics is to be installed. This should include standards for benign-environment enclosures wherever these are feasible and cost-effective.
- ★★ 6. With the concurrence of and to the extent authorized by the Military Communications Electronics Board, establish and promulgate standards for the signals to be transmitted or interchanged in cooperative systems, such as communications, navigation, and identification systems.
- ★★ 7. Review Service forecasts of electronic equipment needs in order to determine those types and classes to which uniform standards should be applied, and act to ensure that they are applied.
- ★★★ 8. Establish and promulgate DOD standards for the multiplexing and interchange of digital data among electronic equipments within ships and aircraft.
- ★★ 9. Promulgate policy designed to ensure maximum compatibility of military standards with commercial practices.

★★★ Highest priority; ★★ high priority; ★ priority.

- ★★ 10. Review existing standards and specifications for parts, materials, finishes, processes, and other aspects of the internal design of military electronics to determine which of these should be
 - a. Strictly enforced
 - b. Subject to the substitution of the contractor-validated alternative
 - c. Regarded as advisory only
 - d. Revoked.

The several general design specifications used in most electronics procurement (e.g., MIL-E-16400, MIL-E-5400, MIL-I-983) should receive particular early attention.

- ★★ 11. Issue up-to-date guidance on military utilization of standard commercial LSI and MSI items, with particular attention to the need for multiple sources and avoidance of military-unique designs.
- ★★ DOD Directive 4120.3 can be the vehicle for the establishment of an effective electronic standards organization. In order to accomplish this, the Defense Materiel Specifications and Standards Board should, under paragraph VII B2 of the Directive, recommend the establishment of an Electronic Standards Panel (ESP), with the authority and responsibility to promulgate multi-Service electronic standards and promote the cause of standardization of electronic equipments, subsystems, and systems, both single-Service and multi-Service. The ESP should be given the further authority to establish continuing (as opposed to ad hoc) committees, to which may be delegated segments of the authority and responsibility of the ESP. Once established, the ESP should organize to undertake formulation and promulgation of the policies recommended above.

★★★ Highest priority; ★★ high priority; ★ priority.

C. SOFTWARE; DIGITAL SYSTEM ARCHITECTURE

We give to necessity the praise of virtue.

--Marcus Fabius Quintilicus

The fast-growing application of digital information processing to military operations makes the subject of its cost and reliability an important topic for special consideration in the Electronics-X Study. Two questions have arisen in the course of the study: the serious problem of software cost escalation, and the best directions, if any, for computer standardization.

In subsequent paragraphs, it will be shown that these two questions are closely coupled. The amount and complexity of software required are related to the selected processor architecture; and standardization, if judiciously accomplished, can permit structuring of processors specifically oriented to the problems to be solved and can minimize the required software without jeopardizing flexibility.

1. Software

For the purposes of this discussion, software includes computer programs and their documentation and excludes the logic design of processor hardware. The software "problem" is in fact many problems: software is often excessively costly, late in completion, poor in performance, and "unreliable." Its development status is inadequately visible.

Some of these difficulties can be discussed in quantitative terms. For example, software cost has become a very substantial portion of system cost in military electronics. According to Barry W. Boehm²⁶ of the Rand Corporation, the Air Force expended between \$1 billion and \$1.5 billion on software in 1972--about three times its expenditure on computer hardware. The Worldwide Military Command and Control System is estimated to require \$722 million for software, as opposed to \$50 million to \$100 million for hardware. Other examples of high software cost are \$200 million for the IBM OS/360 and \$250 million for the Semi-Automatic Ground Environment (SAGE).

Despite the fact that the ratio of software to hardware costs is already high, that ratio can be expected to increase unless new approaches are undertaken. Hardware cost per function is decreasing rapidly as technology advances, but software productivity, despite regular progress, is not keeping up. According to Beum and Levin,²⁷ software productivity has approximately doubled over the last 15 years, while hardware throughput (instructions per second per dollar) has improved fiftyfold. Williman and O'Donnell²⁸ point out a reduction in 1-microsecond-access-time memory cost by a factor of 1000 in 10 years.

Quantitative indications of the software "unreliability" problem can be discerned from the approximate distribution of effort²⁶ in software development, which is remarkably uniform for large-scale systems:

Program analysis and design (after the functional specifications of a system have been completed)	34%
Program coding and auditing	18%
Program integration, checkout, and test	48%.

The 48 percent of the effort expended in software integration, checkout, and test illustrates the extent of the difficulties in correcting functional and coding errors. When the software is finally delivered as part of an operational military system, some of these errors, hitherto undiscovered, come to light in operations. Hence the term software "unreliability" is a euphemism for design errors; software, unlike hardware, is seldom subject to spontaneous failures due to imposed environmental stresses.

In hardware, the expected failure rate and the cost are proportional to system complexity or parts count. In software the situation is analogous: the number of errors to be expected in a program and the cost of the program are proportional to the number of instructions. Thus, the prime step in cutting the cost and increasing the reliability of software is to reduce its complexity. To accomplish this reduction, there are three fundamental possibilities:

1. Reduce and simplify the functional requirements of the system.
2. Write the program in a high-level language to cut the number of instructions programmers must write.
3. Improve the match between the hardware and the problem to be solved.

The latter step brings out the importance of a thorough preliminary system design, taking into account not only the architecture and capabilities of the hardware to be provided but also the extent and nature of the software to complement it. It must be recognized that the complexity and extent of the software may often be considered a measure of the mismatch of the hardware to the problem.

Nowhere else in the electronics arena is the mismatch of the hardware to the problem so evident as in tactical data processing. In communications system design, intense preliminary design effort is undertaken to ensure a proper match. The communications medium is analyzed for its attenuation, reverberation, frequency response, and noise characteristics. The most appropriate operating frequency range, channelization, and signal structure are determined by analysis; power and sensitivity requirements are determined; and transmitters and receivers are designed to match the needs. Similarly, in sonar and radar system design, the volumetric coverage, the medium, the unwanted background reflections, the jamming potential, and the target characteristics are analyzed, and the transmitter, receiver, antenna, scanning system, signal structure, and moving-target-indicator system are then designed. In contrast, the design of military tactical data systems, with only a very few exceptions, begins with the selection of a "general-purpose" computer because it is "flexible," because it exists (perhaps as a military "standard"), or because it is hoped to be about to come into existence. It is a peculiar characteristic of the "general-purpose" computer selected that its design and structure are almost always totally uninfluenced by the problem to be solved.²⁹ If carefully chosen, the computer may have enough speed and memory capacity, but it is almost universally a single-instruction-stream, single-data-stream sequential machine--a descendant of what John von Neumann developed

in 1946, brought to a high state of evolution by manufacturers of general-purpose machines to satisfy a wide variety of customers who have an enormous diversity of scientific and business problems to be solved.

After the computer has been selected, the arduous task of matching it to the tactical problem begins. Quoting R. Turn of the Rand Corporation,³⁰ "In the past, software techniques have been used to compensate for hardware deficiencies in a number of CC (command and control) data-processing systems. Such deficiencies generally have been associated with computational speed, rigid system design, and long lead-time delivery. These and other factors have resulted in an information processing cost distribution of 70% for software and 30% for hardware in many large Air Force programs."

In the next section (Section IV-C-2), we shall discuss developments that permit constructive approaches to a better matching of the hardware and the problems to be solved. For the moment, we confine our discussion to reducing costs and improving reliability in the conventional approach to development of military digital data-processing software.

There appear to be seven principal sources of excess cost in software development for tactical data-processing systems:

1. Selecting hardware and starting programming before the system is designed in detail--that is, before the system functions, organization, inputs, outputs, and transfer functions are thoroughly defined. The flexibility of the digital computer is used as an excuse to procrastinate in system design.
2. Overburdening the central processor with tasks that can be accomplished by specialized peripherals.
3. Selecting too small a central processor, with consequent overutilization of the computer and resort to bad programming practices.
4. Program overintegration, which makes changes difficult.
5. Lack of adequate discipline in software development.

6. Developing a new high-level programming language for every job.
7. Starting programming before the computer design is complete.

The importance of completing system design in detail before starting coding is well recognized by data-processing software experts. Intermixing these two aspects of system development leads to uncertainty, confusion, rewriting, and patching of large blocks of code. Naturally, were dedicated, special-purpose devices used, this problem would be alleviated at the outset, because the algorithms to be mechanized must be thought out in detail before the hardware can be built. Where general-purpose computing is employed, the same processes should be thought out completely and specified in detail before coding starts.

There is a tendency to reserve all difficult processing functions in a tactical system for accomplishment in a central digital computer because "it can do anything." Besides deferring the design of important functional elements of the system, this syndrome causes the aggregation of problems to an extent that can be overwhelming to programmers, with the result that more computing capacity may be needed than is available. Further, when diverse functions are mixed in a single machine, there is likely to be competition by these functional elements for priority attention. Isolating functions that can be accomplished elsewhere and providing peripheral dedicated special- or general-purpose devices to perform these functions can greatly ease the software problem.

As utilization of the capacity of a general-purpose computer approaches 100 percent, the programming problem becomes increasingly difficult. To squeeze the program down so that it will fit within available storage-space or computing-time restrictions requires tightening the coding and perhaps using questionable tricks to shorten the program and minimize the use of core. This process is very costly of coding effort (Fig. IV-5). It is much preferable, from the standpoint of cost tradeoffs, to provide a computer of about 50 percent excess capacity, so that the program can be decomposed and written in well-defined modules that are highly independent of each other and not overly integrated.³¹ Program

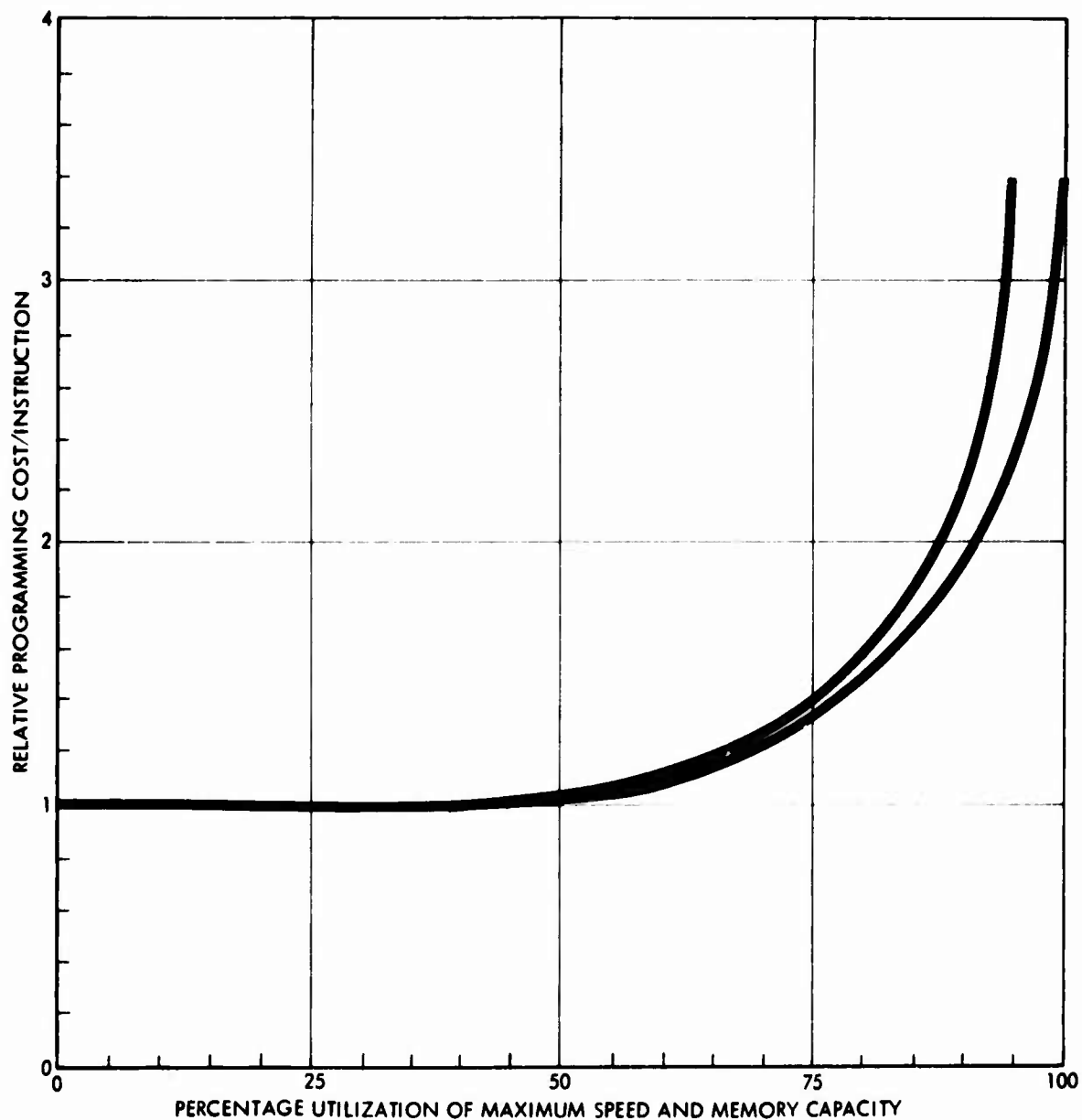


FIGURE IV-5. Programming Costs as a Function of Utilization of Maximum Available Computer Speed and Memory (Source: Ref. 28).

overintegration is a natural tendency of programmers, in any case, and it has the serious fault that the insertion of needed changes characteristically reverberates throughout the program, inducing many further changes and more cost.

Strict discipline of programming operations has only recently been recognized as a necessity if costs are to be controlled and program errors are to be minimized. The kind of discipline imposed is analogous to that traditionally employed in hardware development. "Structured programming" is one such disciplined approach. Specifically, a program can be visualized as a pyramid with control programs at its apex and functional sub-routines at its base. Structured programming uses the "top-down" approach, in which the effort starts with programmers laying down the executive control system and specifying the blocks of program required in the next lower layers. The work progresses down, from layer to layer, with functional routines specified in early phases but not actually coded until the base is reached. The main constraint imposed on program writing is the elimination of the unconditional transfer ("go-to" instruction), which has the unfortunate property of referring to a part of the program over which the programmer has no control.

The invention of new or modified high-level languages in which to program, in the interest of "efficiency," has the unfortunate effect of destabilizing a system that is already only conditionally stable. New compilers must be evolved and verified; already developed routines that might have been conveniently transferred from existing program libraries become unusable.

Initiation of programming before the computer design is complete is clearly wasteful, because even minor machine changes may require extensive program revision.

a. Findings

- Software costs have exceeded hardware costs by large factors in some military systems using general-purpose computers. Boehm, of the Rand Corporation, reported that the Air Force in 1972 expended between \$1 billion and \$1.5 billion on software (that is, computer

programs and associated documentation)--more than twice its expenditures on computer hardware.

- Software developments are frequently behind schedule, causing other costs to spiral.
- Software "unreliability" is a euphemism for software errors.
- The complexity and extent of the software may well be a measure of the mismatch between the hardware and the problem; conversely, by properly designing and structuring the processor, the software problem can be mitigated.
- The major sources of excessive software costs in conventional systems employing central uniprocessors are the following:
 1. Selecting hardware and starting programming before the system is designed in detail--that is, before the system functions, organization, inputs, outputs, and transfer functions are thoroughly defined. The flexibility of the digital computer is used as an excuse to procrastinate in system design.
 2. Overburdening the central processor with tasks that can be accomplished by specialized peripherals.
 3. Selecting too small a central processor, with consequent overutilization of the computer and resort to bad programming practices.
 4. Program overintegration, which makes changes difficult.
 5. Lack of adequate discipline in software development.
 6. Developing a new high-level programming language for every job.
 7. Starting programming before the computer design is complete.

b. Recommendations. To reduce costs of software in processors employing conventional general-purpose machines, our recommendations are:

- ★★★ Complete the design of the system and the basic program structure in substantial detail before making major commitments to hardware or coding.
- ★★ Limit the aggregation of problems to be solved on a central machine; as an alternative, decentralize processing by providing peripheral special-purpose devices (either analog or digital) or separate peripheral general-purpose machines to perform specific separable functions.
- ★★ Select a processor of adequate size to permit underutilizing the computer; write highly modular programs; emphasize structure and overall efficiency rather than hardware efficiency alone.
- ★★ Use rigorous discipline in software development, such as the top-down Structured-Programming approach.
- ★★ Use a standard well-established programming language with which programmers are thoroughly familiar. Use the highest level language appropriate to the task at hand, but avoid the unnecessary development of a unique language.
- ★★ Defer coding until the computer design is substantially complete and firm, except for that necessary to verify hardware-software design compatibility.

2. Digital System Architecture

Quoting Turn,³⁰ "Rapid advances in semiconductor components and packaging have increased logic-circuit and memory speed as well as reliability; at the same time, they have reduced size, weight, and power requirements. Quantity production of large-scale integrated (LSI) circuits and medium-scale integrated (MSI) circuits not only promises a cost reduction but also makes it economically feasible to produce computer systems having a variety of architectures. These new architectures can increase computing speeds several orders of magnitude over the conventional uniprocessor. At the same time, it has become feasible to use hardware to provide additional

★★★ Highest priority; ★★ high priority; ★ priority.

built-in features such as microprogrammed control, data management instructions, hardwired elementary function execution, and sophisticated look-ahead capability...Hardware architectural features could be and are expected to significantly improve the complex software problems that beset the present CC data-processing systems. For example, floating-point arithmetic, provided by programming in many of the contemporary airborne and spaceborne computers, can be expected to be hardwired into all future CC computers. Other utility, support, and operating system routines that can be expected to be mechanized by hardware include the compiler, compartmentation procedures for data security, and executive and operating systems."

Beum and Levin²⁷ predict "the use of hardware to perform traditional software functions through the use of random logic nets in LSI hardware for floating-point arithmetic, multiply and divide, square root, fast Fourier transform, priority coding-decoding, and coordinate transformation; table look-up implemented in ROM for multiply-divide, code conversion, BCD arithmetic, character generation for displays, trigonometric functions, transducer calibration, etc.; and microprocessors (off-the-shelf LSI components providing a library of hardware subroutines) to be used for memory paging, vector multiply, fast Fourier reprocessing, digital filtering, output formatting, etc."

The following hypothesis is offered by Beum and Levin:²⁷ "By 1980 digital information processing hardware, based on LSI technology, will be available at very low cost. For all practical purposes, it will be free."³² Beum and Levin state the airborne-processing implications of this hypothesis as follows:

1. The use of a distributed hierarchy of dedicated processors containing both logic and memory where the emphasis is on functional independence rather than on efficient use of storage, CPU, I/O and concerns of weight, size, and power. System throughput will be achieved by simultaneous operation of many simple processors rather than resource sharing in a few high performance processors....
2. The minimization and/or elimination of airborne software through the extensive use of firmware in read only memories with internal logic such as "CAMS," "stacks," and "queues." This does not

infer the elimination of the "software problem," the need for improved software production standards and techniques. Software development will remain a major part of the development cycle. Conversion of software to firmware and hardware will be a design goal and implemented as part of the incremental test and integration process on the "hot-test-bed."

3. The incorporation of fault detection, internal failure diagnostics, and redundancy of each hierarchical level along with "state" reporting and recording to support maintenance actions. This capability will increase reliability and system effectiveness and involve only minimal cost in dollars, weight, space or power utilization.*
4. Life-cycle system costs and total defense budget dollar savings would be achieved through the availability of dedicated information processors compatible with standard interface and communications requirements. This would also alleviate retrofit and re-configuration problems and would permit common elements (sensors, displays, actuators, data bases, processors, and the like) to be used for various missions and in different vehicles.

With the cost of data-processing hardware--logical and storage elements--steadily declining, while the cost of software increases, the automatic assumption that a single, central, conventional, general-purpose, programmable uniprocessor is the appropriate choice for tactical systems requires re-examination. In earlier times, size, weight, and cost of computing machinery demanded that logical and storage elements be time-shared under program control so that they could be efficiently and economically used. Continuing this approach with larger and faster machines in an epoch of high programming labor costs can be expected to lead to more extensive, costly, and unreliable software. In contrast, the advent of large-scale integration, by which complex algorithms together with memory can be implemented in hardware on a single chip, makes it possible, with a minimal sacrifice of size, weight, or cost, to assemble dedicated devices to perform separately, on a full-time basis, functions that have heretofore been time-shared on a general-purpose machine. A large part of the software, that associated with interrupts and the programmed time-sharing of logical and arithmetic elements, can thus simply be eliminated through planned "inefficiency" in the application of hardware.

*This assertion by Beum and Levin is disputed by those who counter that the added complexity of internal failure diagnostics may cause an overall reduction in reliability.

The hardware architecture envisioned by Beum and Levin as an excellent match to the avionics data-processing problem is essentially a three-level hierarchy of independent, dedicated processors, as shown in Fig. IV-6. At the lowest level, processors are operating on sensor outputs to deliver predigested data to the next level, the "functional" processor. The functional processor combines and correlates data from sensors--for example, in an aircraft, the several sources of navigation data, including inertial measurement unit, doppler navigator, LORAN, VOR/DME radio altimeter, and air data. Another functional processor might be dedicated to operate on the preprocessed sensor outputs for fire-control purposes. Finally, at the highest level of the hierarchy is a processor that monitors system operation, keeps diagnostic records, and provides to functional processors from main memory the data required for their operation--for example, latitude, longitude, and channel of nearby VORTAC stations, and ammunition status and ballistic data on remaining weapons (Fig. IV-7). The reverse information flow in the hierarchy provides, at the lowest level, signals to actuators and displays.

According to Williman and O'Donnell,²⁸ "Having special-purpose processors associated with the sensors offers advantages in minimizing the communication bit rate, in reducing interrupts and overhead in the central processor, and in having one subcontractor responsible for the sensor mechanization and software associated with the sensor. The subcontractor can thus integrate the hardware and software on a subsystem level. This can decrease the system contractor's programming and system-integration effort." The structure described is a variation of what is sometimes known as "federated" architecture, in which computers operate independently. The dedicated processors may be either microprogrammable general-purpose machines or special-purpose machines. The data buses conveying information between sensor/actuator and functional computers are standardized as to speed and format, as are the data buses between functional computers and the monitor level.

The kind of standardization that makes sense in such a structure is on three levels. On the first level is the formation of a library of standard LSI processing elements, comprising algorithms and memory, from

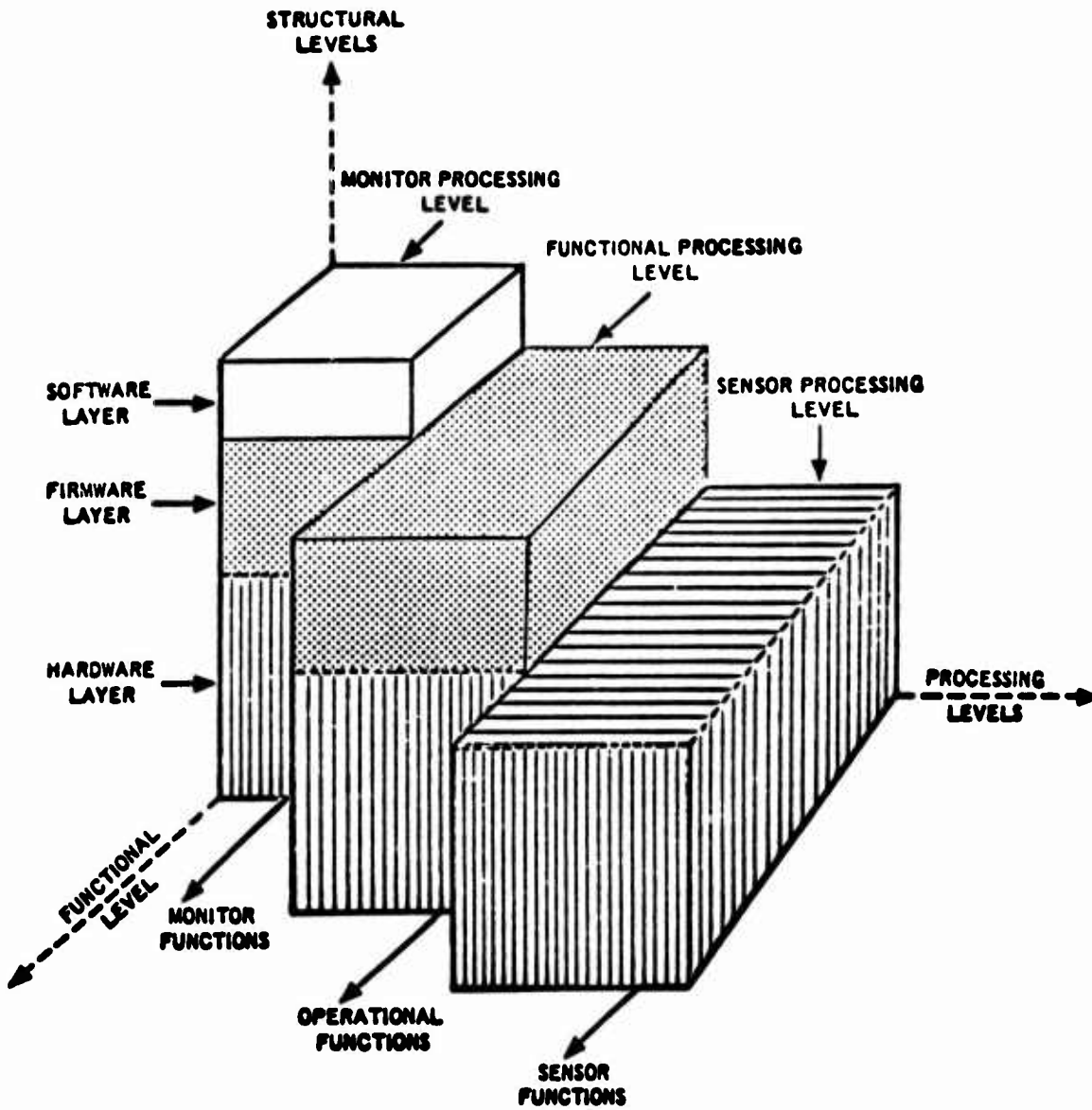


FIGURE IV-6. Three-Dimensional Representation of the Projected Avionic Information System

which processors can be synthesized. Such a library is just beginning to evolve as a result of commercial pressures.

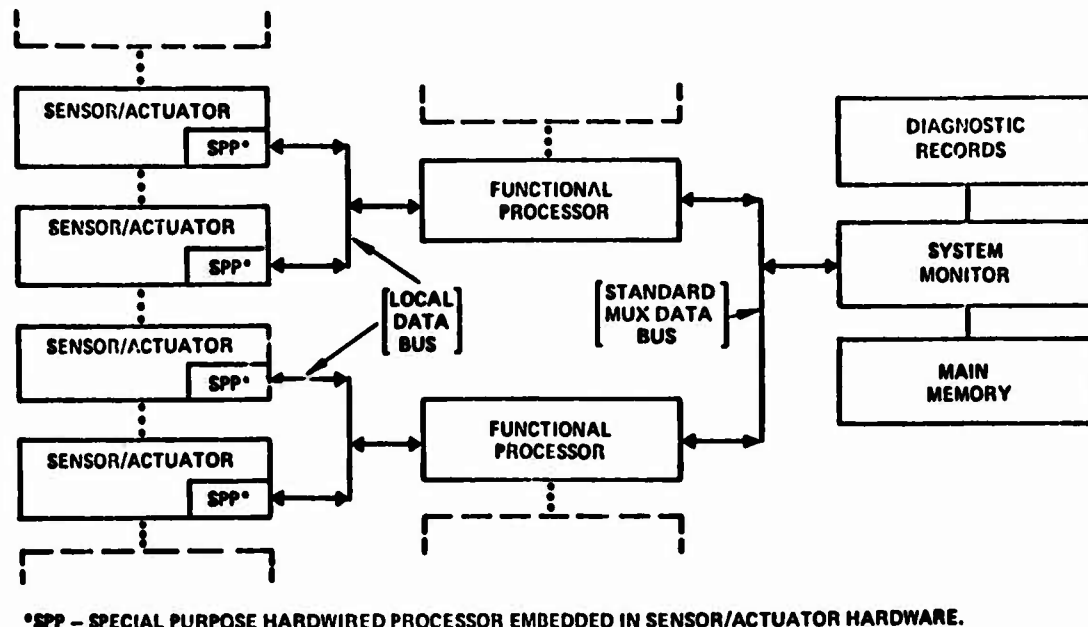


FIGURE IV-7. Projected Avionic Information System Architecture

On the second level is the form-fit-function standardization, discussed earlier, that permits interchange of competitive units of different manufacture.

On the third level is the standardization, across Service lines and for a diversity of applications, of data-interchange speeds and formats for multiplexed digital communication among sensors, actuators, processors, controls, and displays.

An adequate library of standard LSI processing elements can permit the structuring of processors specific to the problem to be solved. One example is the associative array processor, which appears to have extensive

application to large-volume military tactical information storage, retrieval, processing, and data distribution systems. An associative processor is a single-instruction-stream, multiple-data-stream structure, in which each word in the associative memory unit has its own usually simple serial processing unit.³⁰ Processing operations are performed concurrently by all these processing units. Logic is included as an integral part of each bit of each word of memory, permitting simultaneous comparison of the data stored in each word with a reference word. Thus, memory searches can be performed at high speed on all words or on specified subsets of the memory. Such memory systems can be characterized as "content addressable." An important characteristic is that lists can be carried in memory in any order.

Easy storage and rapid search and retrieval are not the only significant characteristics of the associative array processor. The ability to concurrently add, multiply, or divide one array by another, or to perform logical comparisons gives the associative array processor enormous speed advantages over the conventional uniprocessor in many tasks--for example, air traffic control.³³ It is not clear that standard programming languages are directly applicable to the associative array processor.

The foregoing represent just two examples of how the evolution of highly complex LSI processing elements can make possible the development of digital processing hardware that is better matched to the problems to be solved. It must be pointed out, though, that a better match can be achieved even without the use of advanced microcircuit technology by a careful and methodical total-system design.

a. Findings

- No current basis exists for the common assumption that conventional centralized programmable uniprocessors are the most effective or most economical bases on which to structure military tactical data systems.
- The cost of programming is escalating, while the cost of standard computing hardware is plummeting; a new look is needed at the balance between hardware and software in system architecture.

- The advent of large-scale integration has led to the cheap and plentiful implementation in hardware, on single chips, of standardized complex algorithms together with memory. With hardware implementation of a complex algorithm, the need for writing the algorithm in software is eliminated.
- There is a growing library of these hardware-implemented, standard, complex computing functions that makes possible the synthesis of specialized processing units and the elimination of much of the software. The low cost and small size of these units mitigate the need for time-sharing their use, and permit distributed processing, federated architectures, associative array processing, and processing structures specifically tailored to system functions.

b. Recommendations. The principal need in data-processing system design is a reversion to the engineer's approach of first analyzing the problem, then laying out alternate solutions, and then choosing and pursuing the most effective and economical. Specifically,

- ★★★ System-function-oriented processing-hardware structures should be considered as alternatives to the conventional centralized programmable uniprocessor for use in military tactical systems.
- ★★★ The military processing problem should be clearly stated; the system design should be spelled out in detail; and alternate processor architectures and designs should be compared before a hardware approach is selected.
- ★★★ A processor design for each system should be selected and developed that will minimize the combined costs of hardware and software; the allocation of functions between hardware, software, and human operators should be consciously worked out prior to decision.
- ★★ Standard LSI processing elements available from more than one source should be used to the maximum extent possible; development of uniquely military LSI elements should be minimized.

★★★ Highest priority; ★★ high priority; ★ priority.

- ★★ Military laboratories should be encouraged to investigate and develop processor architectures, including federated architectures, that fit military problems and are cost-effective. Conversely, their extensive efforts in the programming of conventional uniprocessors should be reduced to bring the overall program into better balance.
- ★★ Commercially successful processors for which software already exists should be considered for DOD applications wherever appropriate.
- ★★ Formats and speeds for data interchange among sensors, actuators, processors, controls, and displays should be standardized across Service lines and for as wide a variety of applications as practicable.

★★★ Highest priority; ★★ high priority; ★ priority.

D. DESIGN EVOLUTION AND CONFIGURATION MANAGEMENT³⁴

Department of Defense Directive 5010.19 and Instruction 5010.21, together with DOD Standard MIL-STD-480, now govern configuration management. A new Department of Defense regulation, "Configuration Management," is in the last stages of signoff prior to official promulgation.³⁵ It will, when finally approved and issued, establish revised policies and practices applicable to all segments of DOD.

The purposes of configuration management appear to be six:³⁶

1. To ensure that, once approved, a design does not deteriorate by reason of the unilateral introduction by a contractor of inadvisable changes.
2. To maintain specified form-fit-function characteristics of equipment unless there are compelling reasons for change.
3. To avoid changes that increase cost and delay delivery.
4. To ensure that internal equipment changes that may affect interchangeability and installation provisions are recognized and acted upon.
5. To ensure review of safety-related changes, such as aircraft weight, balance, or flight safety.
6. To carefully document successive equipment configurations for purposes of maintenance and to facilitate competitive re-procurement.

The central aspect of configuration management is that certain types of change must be reviewed and approved by the Government before they are undertaken. The central philosophy of requiring Government approval of proposed changes is to protect the Government's interests; thus, the philosophy is basically defensive. The questions that subsequent paragraphs of this section seek to examine are:

1. Are Government configuration management policies consistent with the freedom needed by a supplier-warrantor to make the evolutionary internal design changes he sees as needed to

increase reliability, thus to balance the costs of production and maintenance, both of which he is responsible for?

2. Are Government configuration management practices appropriate --that is, expeditious enough--to permit timely incorporation of changes in electronic equipment that are needed to correct deficiencies in reliability or in other performance?
3. Are Government configuration management policies consistent with design-to-cost contracting, in which the developer is ostensibly free to adjust the performance of equipment under development to match the target production price?
4. Are Government configuration management policies flexible enough to permit design evolution within a form-fit-function specification framework intended to encourage continuing design and price competition among interchangeable designs?

The about-to-be-promulgated DOD regulation covering configuration management will be taken as authoritative and representing the intended updating of current DOD policies. Current practices, on the other hand, have been the subject of specific investigation by W.J. Douglas of Ketron, Inc., and are reported in Electronics-X Subcontractor Report 4.³⁴

One important clause from the forthcoming DOD regulation deserves special scrutiny:

3-2. Change criteria. Engineering changes, waivers, or deviations affecting the Government's interest in the configuration of a CI (Configuration Item) will be limited to those which are necessary or offer significant benefit to the Government. (Underscoring ours)

This clause illustrates a fundamental bias in that it excludes from consideration changes, waivers, or deviations that benefit the contractor but are neither beneficial, disadvantageous, nor necessary to the Government. Such a situation could be expected to arise in the case of a fixed-price supplier and long-term warrantor who found that changes in internal configuration of an electronic equipment would substantially lower the cost of building and maintaining it.

Incorporating such a change would, of course, be desirable from the supplier-warrantor's standpoint, since it would reduce his cost and increase his profit. It could be neither beneficial, disadvantageous, nor necessary to the Government, since the supplier-warrantor would already be under contract to supply and maintain the equipment for a long term under a fixed-price agreement. Thus, the clause provides in certain projected situations a disincentive to contractors to evolve less costly, easier-to-maintain designs through design simplification or the application of new technology.

If the contractor were able to demonstrate that the changed equipment would be more reliable in military use, or if the contractor offered to share the projected cost reduction with the Government, a benefit to the Government would exist, and the change, waiver, or deviation could be considered. However, requiring such a demonstration of Government benefit, we believe, puts an undue burden on the contractor* and reduces his incentive to evolve improved designs. We believe, therefore, that the clause should be changed to read:

3-2. Change Criteria. Engineering changes, waivers, or deviations in the configuration of a CI will be limited to those which are necessary, or offer significant benefit to the Government, or are substantially beneficial to the contractor and not prejudicial to the interests of the Government.

Changes are classified by MIL-STD-480. Class I changes are nominally defined as those that affect form, fit, function, price, delivery, safety, or support, while others are Class II. Yet, from Fig. 1 of the about-to-be-promulgated DOD regulation, a product baseline is established at the end of full-scale development and test of prototype items, and from Paragraph 3-3 of the same source,

Once the product baseline is established, all changes to an item down to its lowest reparable level shall be processed as Class I. (Underscoring ours)

*A fixed-price supplier or warrantor has undertaken considerable risk, his price has been established competitively, and he should not be required to share the fruits of his cost-reduction effort.

The significance of this is that all changes to items for which a product baseline is established, not just important changes, must be processed as Class I, which means that they must undergo the full Government engineering-change-proposal (ECP) approval process before being implemented. In contrast, when a change is classified as Class II (a decision that can be confirmed by the Government plant representatives at the contractor's plant), this lengthy and costly submission, review, and approval process should be avoided.

The problem is in the timeliness of Service processing of Class I change actions. Although the proposed configuration management regulation meticulously enunciates a policy of promptness, in actual practice the time required to implement a change via the ECP process can vary over a wide range. The approximate magnitude of this time period can be established by examining some of the data made available for this study.

In 1970, the GAO examined the delay being experienced in processing ECPs throughout the Services.³⁷ Table IV-5 shows data extracted from a sample of 547 ECPs. The results indicate that 81 percent of all ECPs required more than the DOD standard of 45 days to process. The GAO study further showed that sequential processing and procedures having ill-defined milestones were largely responsible for the delays. The ECPs were not being internally tracked. The major effect of the delay is the increased cost of implementing in the field changes that could have been caught on the production line by expeditious processing of the ECPs.

The Services have taken steps to improve the processing of ECPs. Recent modifications to the configuration management manuals of the Services have defined milestones from receipt of ECP up through contract agreement. In the Army Electronics Command at Fort Monmouth, detailed ECP statistical data are maintained in the Production and Procurement Directorate. An analysis of the data has indicated that over 70 percent of the ECPs are processed within 45 days. However, when contractual action is required, some 6 or 7 months elapse between

ECP approval and the initiation of a contract to actually accomplish the approved change. This time is taken up in the process of procurement, which involves submission of a detailed proposal, contract negotiations, and the issuance of a contract modification.

TABLE IV-5. ECP DELAY^a

<u>Agency</u>	<u>Number of ECPs Sampled</u>	<u>Average Duration of Processing, days</u>	<u>Percentage Distribution</u>				
			<u>≤ 45 Days</u>	<u>46- 90 Days</u>	<u>91- 180 Days</u>	<u>181- 360 Days</u>	<u>>360 Days</u>
Naval Air Systems Command	292	158	9%	21%	39%	26%	5%
Army Aviation Systems Command	180	103	27	24	34	15	0
Aeronautical Sys- tems Division, Air Force Sys- tems Command	75	92	37	32	19	9	3
Overall	547	131	19%	24%	34%	20%	3%

NOTE: Overall, processing time for 81 percent of the ECPs exceeds the DOD standard of 45 days.

MIL-STD-481 (Configuration Control): 45 days for routine ECP
15 days for urgent ECP
1 day for emergency ap-
proval

^aSource: Ref. 37.

For another view of the ECP process, the ECP files at the Naval Air Systems Command (NAVAIR) were consulted. At NAVAIR, the program manager decides within 5 days whether or not to pursue the ECP. At this time, a Change Control Board (CCB) change request is completed, in which information from the ECP is aggregated for use by the CCB on NAVAIR Form 13050/2. NAVAIR further breaks out the CCB request forms by contractor so that the contractors for electronic and avionic systems can be looked at separately. A group of over 100

CCB electronics and avionics change requests acted upon during FY 1972 were examined. Of these, 84 produced usable data.

The average processing time for these ECPs is shown in Table IV-6. The breakdown is given according to three categories:

1. Production changes
2. Production and retrofit changes
3. Retrofit changes.

The results in Table IV-6 indicate a long delay, particularly for changes involving cost increases. For no-cost ECPs, the delay varies from 1.6 to 2 times the 45-day target. For cost-increase ECPs, the delay varies from 2.4 to 4.2 times the 45-day target.

TABLE IV-6. PROCESSING TIME FOR ECPs AT NAVAL AIR SYSTEMS COMMAND, FY 1972

	<u>Number of Changes</u>	<u>Average Processing Time, days</u>
<u>Production Changes</u>		
Cost Increase	10	122
No Cost	6	92
<u>Production and Retrofit Changes</u>		
Cost Increase	12	190
No Cost	30	74
<u>Retrofit Changes</u>		
Cost Increase	26	106
No Cost	--	--

It is difficult to conclude, on the basis of these observations, whether the ECP approval process is dilatory or excessively detailed, since the complexities surrounding the changes were not amenable to investigation within the time available for this study. It is clear, however, that the average time required for approval is excessive from the standpoint of realizing the benefits of a change as early as possible in the course of production. The delays are, of course,

compounded when the change originates with a lower-tier subcontractor and must be processed through the hierarchy.

Past experience indicates that the configuration of electronic equipment at the end of full-scale development (that is, at the start of production) has simply not received enough cumulative testing to ensure adequate field reliability. It has been demonstrated further³⁸ that reliability growth slows drastically when the freedom to incorporate corrective changes is sharply restricted. Thus, the clause previously quoted from Paragraph 3-3 of the regulation exerts an impeding effect on reliability growth by requiring recourse to a lengthy ECP approval process just at the time when equipment appears in the field and operational use is beginning to expose the equipment's previously hidden deficiencies.

The clause is evidently based on the premise that the Government is to perform equipment repair, since it refers to "changes...down to ...lowest reparable level," and the object is apparently to avoid, impede, or expose changes that would require revision of stocks of repair parts established by the Government. Clearly, therefore, it is inappropriate to the situation in which a supplier-warrantor has undertaken responsibility for maintaining equipment and, accordingly, should have as much freedom as possible to reconfigure the equipment internally to improve its reliability and cut maintenance costs. Moreover, the clause is a serious disincentive to reliability growth, regardless of who is responsible for equipment repair.

In order to encourage reliability improvement and to avoid delays in putting reliability-oriented changes into effect, we prefer the use of two baselines for electronic equipment: a tentative product baseline, established at the end of full-scale development, and a final product baseline, established by the Government after field-reliability objectives have been attained or at such other time as the Government believes that further internal configuration changes should be discouraged. The second and third sentences of Paragraph 3-3 should, we believe, be replaced by the following:

An engineering change to a privately developed item or to an item for which a tentative product baseline has been established shall be classified Class I when it affects form, fit, function, safety, or increases cost or delivery schedule of the item; otherwise it shall be classified Class I. Once the final product baseline is established, all changes to an item down to its lowest repairable level shall be processed as Class I.

Were this change made, definitions of tentative and final product baseline configurations would be needed in Chapter 2 of the proposed regulation on configuration management. To establish a tentative product baseline when full-scale development is completed and production is begun, and to defer establishing the final product baseline until field experience has been obtained (or until the Government wishes to take over equipment maintenance from a long-term contractor); a contract would state the dates or conditions upon which the two baselines would become effective. The flexibility to do so is already provided in the proposed regulation (Paragraph 1-2d). The change proposed here would have no effect on the requirements for maintaining configuration documentation and records. It would be appropriate for the Government, of course, to defer procurement of a full stock of spare parts until the final product configuration had evolved.

Paragraph 1-5a(3) of the proposed regulation states:

CIs, during Full Scale Development, will be subjected to configuration management, principally at the system/prime item level as defined in MIL-STD-490.

This requirement for configuration management appears to be inconsistent with the flexibility needed in design-to-cost development contracts. As discussed in Section III-B, the object of design-to-cost development is to achieve by iterative adjustment the best possible match of requirements, developed product, and target production cost. To accomplish this end, a minimal imposition of formalism on communication between contractor and Government is desirable, particularly as regards engineering changes. We therefore believe that,

even though the regulation contains words indicating need for flexibility in application of the configuration management process, the following sentence should be added to Paragraph 1-5a(3):

Exception: Items in the process of full-scale development under design-to-cost contracts will not be subject to formal configuration management procedures except to the extent specifically called out by contract.

The proposed regulation on configuration management appears to be consistent with the application of form-fit-function specification and interface standardization. The regulation also appears to be consistent with the policies and practices, proposed elsewhere in this report, of periodic design improvement, block changes, and continuing design competition between similar designs.

1. Findings

- A new DOD regulation, "Configuration Management," is in the last stages of signoff prior to official promulgation. It will establish policies and practices applicable to all segments of DOD. As it now stands, this draft regulation still has the following drawbacks:
 1. It unduly restricts the freedom required by a supplier-warrantor to make the evolutionary internal design changes he sees as needed to increase reliability and thus to decrease the sum of unit production cost plus unit contractor maintenance warranty cost.
 2. It imposes a configuration baseline at the end of full-scale development. Thus, all changes after this point--and experience shows there are many--must undergo the formal configuration-change processing routine, a routine that has often led to delays in the past despite good intentions and reasonable procedures.
 3. Its effect would be to restrict the freedom required to make tradeoffs between cost, performance, schedule, and quantity in design-to-cost contracts.

- The draft regulation properly emphasizes the requirements for meticulous configuration-status accounting and keeping technical documentation current with the configuration.

2. Recommendations

★★★ The about-to-be-promulgated DOD regulation on configuration management should be adopted with the following modifications:

1. It should specifically permit consideration of changes that are of benefit to the contractor and not detrimental to the Government.
2. It should establish two product baselines, the first a "tentative" one at the end of full-scale development, and the second, "final" one when the design has been adequately stabilized (see below).
3. It should permit internal equipment changes that do not affect form, fit (compatibility and interfaces), function, price, or delivery to be classified Class II (as defined in the regulation) in order to facilitate the change approval process until the "final" product baseline is invoked by the Government.

★★★ The Government should defer invocation of the final product baseline, as applicable to electronic equipment, until field reliability objectives have been achieved, or, in the case of equipment under contract maintenance warranty, until the warranty period is about to end and the Government is about to take over maintenance from the warrantor.

★★★ The Government should defer full spares stocking until after the final product baseline is invoked.

★★★ Highest priority; ★★ high priority; ★ priority.

E. PROJECT MANAGEMENT

*Never tell people how to do things.
Tell them what to do and they will
surprise you with their ingenuity.*

--George Smith Patton, Jr.

As a result of findings by Electronics-X teams that insufficient data were available to permit the setting of firm cost targets for design-to-cost (DTC) projects, it was concluded that tradeoffs between performance, cost, schedule, and quantity had to be made throughout the RDT&E phase of a DTC program, and only at the end of the RDT&E phase could the unit production cost be set in binding contractual terms. During the production phase, a modicum of flexibility is still required so that tradeoffs between performance, schedule, and quantity can be made as the program progresses (Section III-C). This raises the question whether the project manager (PM) can be expected to make the required tradeoffs.

To answer this question, we have briefly reviewed project management, as applied to electronic subsystems, through discussions with managers and staffs of 21 project offices: 12 Navy, 6 Air Force, and 3 Army (Table IV-7). Despite the unequal representation of the different Services in these discussions, we believe our review has attained a reasonable balance of the views of the Services.

The major emphasis of the discussions was on the ability of the project manager to make practical tradeoffs between cost, schedule, and performance (including reliability, availability, and maintainability), and usually included the following issues:

- Project manager's authority versus his responsibility
- Tradeoff capabilities and limitations
- Practical significance of project manager's rank
- Selection of project office personnel
- Career opportunities in project management
- Levels of management between project manager and Service Secretary

TABLE IV-7. PROJECT MANAGEMENT OFFICES VISITED DURING STUDY

Project	Service	Command or Division	Project Office	Layers of Authority Between Project Manager and Service Secretary	Project Manager
Ship and Air Systems Integration (SASI)	Navy	NMC	PMA-15	2	Capt. R. Boh, Jr.
Navy Space Project	Navy	NAVELEX	PME-106	3	Adm. K. K. Gaiger
Satellite Communications	Navy	NAVELEX	PMA-106-1	4 (Asst. PM)	Cdr. J. B. Wheeler
Special Remote Sensor System	Navy	NAVELEX	PME-121	3	Capt. R. A. Pettigrew
REMSON	Navy	NAVELEX	PME-107	3	Capt. E. R. McDonald
Low-Cost Electronic Warfare	Navy	NAVELEX	PME-107X	4 (Asst. PM)	Cdr. R. Hullender
Special Communications	Navy	NAVELEX	PME-117	3	Capt. W. C. Cobb
Sonar	Navy	NAVSHIPS	PMS-302	3	Capt. E. L. Alderman
T-14/PHOENIX	Navy	NAVAIR	PMA-241	3	Adm. L. A. Shead
HARPOON	Navy	NAVAIR	PMA-258	3	Capt. C. P. Ekas, Jr.
Cruise Missiles	Navy	NAVAIR	PMA-263	3	Capt. W. M. Locke
Versatile Avionic Shop Test (VAST) System	Navy	NAVAIR	PMA-238	3	Capt. W. Spangenberg
Tactical LORAN	Air Force	ESD	Deputy for Communications & Navigation (YS)	4	Col. M. Alexander
DOD PIMS/TRACALS	Air Force	ESD	Deputy for Communications & Navigation (YS)	4	Col. L. Giesy
TAN-19	Air Force	ESD	Deputy for Surveillance & Control (OC)	4	Col. T. Doss
OTH Radar	Air Force	ESD	Deputy for Surveillance & Control (OC)	4	Col. D. W. Lambrecht
Advanced Airborne Command Post (AABMCP)	Air Force	F3D	Deputy for AABMCP	3	EG L. W. Cameron
Airborne Warning and Control System (AWACS)	Air Force	ESD	Deputy for AWACS	3	EG L. A. Skantze
Army Tactical Data System (ARTADS)	Army	AECOM	-	3	EG A. B. Crawford
Army Tactical Communication System (ATACS)	Army	AECOM	-	3	Col. J. P. Dobbins
Army Satellite Communications	Army	AECOM	-	2	Col. L. D. Wainstead

- Demand for briefings by project manager
- Organization of project office.

The results of this brief review are reported fully in Ref. 39 and are summarized below.

In general, there are four types of project managers:

1. Project managers for major systems that are primarily electronic (Class I* electronics)
2. Project managers for major systems of which electronics forms an important subsystem (Class II* electronics)
3. Project managers for single electronic subsystems (Class II or III* electronics)
4. Multiprogram project managers ("basket" PMs), who manage a number of similar or related electronic subsystems (Class III electronics).

Project managers for major weapons systems such as the F-14 must usually adhere to rigid development schedules imposed by important system components other than electronics--the airframe, for example. Project managers for major systems have considerable clout on the one hand and great visibility on the other. Errors are highly visible and subsystem modifications are discouraged, since they might cause costly slips in overall schedules. Long-term commitments are required, and overall system schedules permit little change in electronic subsystem configurations if they affect interfaces with other parts of major systems. A project

*Classes of electronics as defined in Section III-B-4:

- Class I: Major systems, by DSARC criteria, 50 percent or more of whose cost is in electronics.
- Class II: Electronic subsystems of major (DSARC) systems, representing 10 percent or more of total system cost, and included within and scheduled with the major system acquisition.
- Class III: Electronic subsystems, multipurpose in character, developed independently for use in many major systems, and themselves below the criteria for major systems.
- Class IV: Other electronic systems and devices, below DSARC criteria, that do not fall into any of the above categories.

manager for a major weapons system often prefers a firm and unchanging specification for an electronic subsystem unless changes in that subsystem are required by and essential to the weapons system. Thus, continuing tradeoffs that might improve an electronic subsystem are less important than the availability of a set of electronic subsystems to choose from whose costs and interface characteristics are firmly established.

Subsystem project managers are of lower rank and have lower visibility but somewhat greater flexibility than major-system project managers. One of their main problems, because of the limited life of their projects, is getting and keeping good personnel. This can affect their capability for making tradeoffs, even if the authority to do so is granted them.

The multiprogram project manager runs a perpetual project office that manages the development of a whole series of related equipments or subsystems. Such a project manager is usually of high rank, often a brigadier general or rear admiral. At any one time, some of the subsystems for which his project office is responsible are entering production, others are in engineering development, while still others are in advanced development. The permanence of the office allows it to attract and keep good personnel. Schedules are somewhat flexible, encouraging some degree of innovation. But if two programs reach a crisis stage simultaneously, the top man is often saturated and may have to shortchange one program to further another.

Tradeoff possibilities in all project offices are limited by:

- Formalized restrictions in the governing documents on reprogramming funds or changing major specifications.
- The origin of the funding (often, each subsystem has a different sponsor)
- Limitations imposed by the project manager's commander (such as the Army Materiel Command limit of \$200,000 on the funds that may be shifted from one program to another).

The most flexible and apparently effective arrangement we saw during our series of interviews involved a multiprogram project office where the

project manager had the authority to reprogram about 15 percent of his total annual DT&E funds among his various programs. His high rank, his forceful personality, and the fact that he had a single "sponsor" were probably responsible for his unusually flexible position.

The need for quick reprogramming of funds from one program to another by the project manager is greatest when tradeoffs between cost, performance, reliability, and schedule must be made at frequent intervals. The need is most evident during the DT&E phase and persists in the OT&E and the LRIP phases. Once the unit production cost is set as part of a production contract, the need for reprogramming of dollars by the project manager disappears, but freedom for the PM to make limited tradeoffs among the other parameters while holding unit production cost constant remains essential.

Some project managers indicated that they had participated in the formulation of original program requirements. Not surprisingly, those project managers generally were enthusiastic about the requirements, had confidence in their legitimacy, and felt able to complete the programs successfully.

1. Finding

- Design to cost is a concept which depends for its success on the flexibility and timeliness of management decisions. Such decisions are usually best made at the project-manager level, provided that the project manager has the requisite authority--for example, sufficient authority to shift funds from one program to another in a multiprogram project office, and thus to defer or eliminate lower priority tasks in one program in order to expedite high-priority tasks in another program. This reprogramming authority is present in some multiprogram offices but is absent in others, largely because different line items in the budget are often controlled by different "sponsors" in the headquarters organization, and each sponsor guards his share of the budget.

2. Recommendations

- ★★★ Use the multiprogram project office ("basket" SPO) structure for all independent electronic subsystem development where a number of related or similar developments can be grouped under one perpetual project manager (PM) to provide a PM of higher rank and greater authority, better project office personnel, more responsive support from functional groups, and more trade-off flexibility.
- ★★★ Provide multiprogram project offices with sufficient flexibility in the use of available R&D funds to allow the necessary tradeoffs by the PM in the development, OT&E, and LRIP phases.
- ★★ Arrange for the project manager or prospective project manager to participate in drafting the operational requirements before developing specifications for subsystems under his jurisdiction.
- ★★ Make available to system project managers catalogs of available electronic equipment that show current price and reliability figures as well as technical descriptions.

★★★ Highest priority; ★★ high priority; ★ priority.

F. DATA COSTS⁴⁰

Significant quantities of technical data are acquired and paid for by DOD each year. Estimates range from \$1.5 to \$2.25 billion annually for contractually required data items, including those for electronics. This is the formal cost charged by contractors for data and does not include the Government's cost associated with requesting, receiving, reviewing, handling, or storing technical data. Contractor and Government personnel indicate that additional costs for data items are charged under other headings to contractor direct labor and are not explicitly included in the data costs as called out contractually. In subsequent paragraphs, the cost of data associated with electronics acquisition will be estimated, the major reasons for obtaining the data will be indicated, and approaches to reducing data costs will be recommended.

To provide the basis for the observations that follow, discussions were held with Army, Navy, and Air Force representatives involved in data management, three electronic equipment contractors were interviewed about technical data, and the Air Force Data Review Action Group (DRAG) Study,⁴¹ which in 1970 examined the data requirements of 28 major Air Force programs, was reviewed and evaluated. Particular attention was paid to the details of four primarily electronics programs covered in the Air Force study. In addition, nine proposals and contracts (five Army, two Navy, and two Air Force) were evaluated for technical-data cost.

1. Data Costs as a Percentage of Program Costs

The Air Force DRAG Study examined all data items on the Contract Data Requirements List (DD Form 1423). The purpose was to eliminate data items, refer them to higher authority for deletion or modification, and modify (the frequency or number of copies of) existing data requirements. The total cost of each of the four electronics programs reviewed by the DRAG Study was more than \$22 million, the data costs ranging from 1.1 percent to 16 percent of program cost. The total data cost for these four programs was \$13.2 million. The DRAG Study recommended changes that could potentially reduce data costs by 16 percent. It was later found that, in fact, a saving of only 1 percent in data cost was realized on these four

programs, primarily because the Study's recommendations came too late to accomplish reductions in the data required under contract. Nevertheless, by highlighting and categorizing data costs, the DRAG Study was of utility.

Evaluation of contracts and proposals revealed considerable variation in data cost from program to program. It was noted that for small RDT&E contracts of \$1 million or less, formal data cost constituted approximately 20 percent of contract cost. Review of Army Electronics Command (AECOM) information indicated that 97 percent of AECOM awards were for less than \$1 million, which accounted for approximately 46 percent of the dollars. It was concluded that the ratio of data cost to program cost for all RDT&E programs averages approximately 10 percent. This ratio was estimated to be 5 percent for production contracts.

2. Data Costs, Categories, and Content

The cost of data for electronic equipment was estimated as follows. The formal cost of all data is \$1.5-\$2.25 billion annually, of which electronics data are estimated at approximately 33 percent of the sum, or \$0.5 billion to \$0.75 billion. Alternatively, estimating electronics data at 10 percent of the \$2.9 billion contracted RDT&E cost and 5 percent of the \$5.6 billion production cost yields a cost of \$0.57 billion annually for electronics data. This last figure is used to estimate the costs of various electronics data categories.

Data can be categorized by the use to which it is put. The allocation of electronics data costs among these categories was found to be as follows:

- Reprocurement: 15 percent or \$85.5 million
- Engineering Validation and Monitoring: 30 percent or \$171 million
- Maintenance and Training: 50 percent or \$285 million
- Administrative and Cost Control: 5 percent or \$28.5 million.

Typical contractor data items included in each category are as follows:

- Reprocurement: Drawings and specifications
- Engineering Validation and Monitoring: Reliability and maintainability documentation, test plans and reports, component selection reports
- Maintenance and Training: Technical manuals, maintenance manuals, operating manuals, provisioning documentation
- Administrative and Cost Control: PERT charts, contract status line of balance reports.

The largest single data cost was found to be for handbooks and technical manuals. The DRAG Study indicated handbook cost to be 53 percent of total data cost for all kinds of equipment programs studied. For electronic equipment programs only, cost of technical manuals was 35-50 percent of total data cost.

3. Data Requirements Generation and Validity

Determination of requirements for the data to be supplied under contract characteristically starts with a request--a "data call"--issued by the Government program manager. Individual specialists in support activities of the development agencies then state their needs and specifications for configuration-management plans, handbooks, reliability documentation, human-factors engineering documentation, drawings, electromagnetic compatibility analysis, progress reports, cost reports, and so on. The aggregated requirements are then sometimes (not invariably) examined by a Data Requirements Review Board, which can add or subtract items but seldom provides a stringent review.

Because the attitude on data is "better to have it and not need it than to need it and not have it," the Contract Data Requirements List often turns out to be far more extensive than is warranted. A recent request for quotations for design-to-cost development of a relatively simple electronic item [Army absolute altimeter AN/APN-209 (Section III-C)] listed 70 required data items, including such items as a radioactive-material report, a maintainability mathematical model, and five nuclear-vulnerability test plans and reports.

The net effect of such massive reporting requirements can be counter-productive. Recognizing that Government review of submitted data must be less than thorough because of the enormous volume submitted, a simple solution for a contractor is to hire hack specialists to prepare, with the least possible expenditure of effort, time, bother, and diversion from the main work, voluminous and plausible-sounding documents whose relationship to the actual project effort is not, and probably cannot be, validated by the Government specialist who reviews them.

It is our conclusion that the submission of massive amounts of written information cannot substitute for direct oral discussions among interested parties and for laboratory testing and measurement of equipment to determine whether its properties meet military requirements. The increasing efforts to make such substitutions appear to further the erection of a communications barrier between Government and contractor as though, somehow, this were a necessary concomitant of an arms-length relationship. Moreover, a sluggish mass of written communications is incompatible with the speed and flexibility required in design-to-cost development and is, as indicated earlier, extremely costly.

4. Potential Data Cost Savings

Four observations have been made by Government and contractor personnel with regard to contractually required data:

1. There is limited availability of DOD personnel to review data items submitted for review.
2. Documentation must be submitted too early to be valid.
3. Many data items overlap.
4. Data are required that have low probable utility.

On the basis of Air Force studies and our own observations, we believe that data costs could be reduced by at least 10 percent, with a resultant saving of \$60 million, by eliminating dubious data requirements, by deferring data procurement until the need is firmly established, by relying to a greater extent on commercial formats, and by deferring the required delivery of provisioning data and technical manuals until the

equipment design has been stabilized. Were all of the Electronics-X recommendations implemented, the reduction in data requirements might amount to as much as 50 percent, or \$275 million.

5. Findings and Recommendations

a. Findings

- The cost of electronics technical data to DOD is very large. It consists of the following: an estimated annual \$600 million formally charged for data; hidden costs charged under the headings of "engineering" or other categories of direct labor; and Government costs entailed in requesting, receiving, reviewing, handling, or storing technical data. On the average, the formal cost of data averages about 10 percent of RDT&E contract costs and 5 percent of production costs.
- The largest cost items are handbooks and technical manuals, which comprise some 35-50 percent of the total data costs for electronics.
- The data requirements are so massive that it is impossible for Government personnel to review the submitted material or to test its validity.
- Discussions with industry representatives show that the reproducible data submitted in response to contract requirements are not the data used for actual manufacture in the contractor's plant; the plant may use numerical control tapes, while the Government data may consist of exquisite india ink drawings on mylar.
- The submission of the data is often required too early to be valid. For example, handbooks and provisioning documents may have to be submitted before the equipment design is stabilized.
- Many of the data items required overlap.

In addition to these observations on the current course of events, it is pertinent to note that, were certain of the recommendations of other sections of this report to be followed, some conventional data requirements would be reduced or eliminated.

equipment design has been stabilized. Were all of the Electronics-X recommendations implemented, the reduction in data requirements might amount to as much as 50 percent, or \$275 million.

5. Findings and Recommendations

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- Many of the data items required overlap.

In addition to these observations on the current course of events, it is pertinent to note that, were certain of the recommendations of other sections of this report to be followed, some conventional data requirements would be reduced or eliminated.

1. Were competitive equipments available from two or more suppliers, the need for reprourement data would be eliminated.
2. If direct transfer of information from developer to second-source supplier were encouraged by suitable incentives, the reprourement data package could be reduced in extent and less rigid in format.
3. If equipments were repaired by contractors under warranty or by specialists at depots, the extensive and explicit instructional documentation required for organizational repair by technicians of limited capability could be reduced, and good commercial-grade handbooks would suffice.
4. If competitive prototyping and test were the bases for acceptance of equipment designs, the need for voluminous in-process validation data would be reduced.

b. Recommendations

- ★ Accept contractor's data format unless there is a demonstrable advantage in specifying a Government format.*
- ★★ Defer the ordering and delivery of contractor data until the need is firmly established.*
- ★★ Delay procurement of spares provisioning, technical manuals and maintenance handbooks until the point of design stabilization is identified and reached.*
- ★★ Scrub data requirements mercilessly through the efforts of Data Requirements Review Boards that include representation of the project manager, the user, and industry.
- ★ Where the equipment future is uncertain, buy options on reprourement data instead of the data itself.

★★★ Highest priority; ★★ high priority; ★ priority.

*Recommendation also made by Electronic Industries Association and contained as policy in DOD Directive 5010.29R, "Data Acquisition Management Program," draft.

The following recommendations, previously made in other contexts, have been recast below to reflect their impact on data costs where applicable.

- Use competing suppliers of interchangeable equipment to reduce the need for reprourement data.
- Use contractor warranties and maintenance to reduce the need for technical and maintenance manuals and provisioning data.
- Rely on competitive prototyping and test as a substitute for voluminous in-process validation data (and as a substitute for myriad detailed specifications).
- As an alternative to formal and highly detailed reprourement drawings and specifications, require less formal drawings and encourage more informal information transfer. For reprourement data, pay a fixed amount for the drawings plus a fixed amount for each equipment successfully delivered by the second source.

G. COST ESTIMATION

Much of the uncertainty exhibited in the ability of DOD to estimate ultimate product or program costs derives from the cost-estimation process itself and the methodology available to the estimator.⁴² It is clear from past cost-estimating experience that improvements are desperately needed in the ability to estimate the future cost of major electronic weapons systems and associated electronic subsystems. As a first step, the existing tools available for cost estimation must be examined to determine their strong and weak points. Then, candidate avenues for improvement can be addressed to improve these existing estimating tools. Finally, areas of estimating uncertainty which exist independently of all efforts to improve estimating methodology must be identified as potential limiting constraints placed upon both expected cost values and residual levels of cost uncertainty.

1. Techniques for Electronics Cost Estimation

The tools available for estimating the acquisition and operations cost for electronic equipment can be classified into four broad methodological categories: engineering, parametric, analogy, and subjective. The engineering methodology for cost estimation consists of a detailed "bottom-up" estimating process that begins with the assignment of cost elements to as many product and program plan details as can be defined by the estimator. Typically, the man-hour and material requirements to design, develop, produce, and maintain a system are identified on the basis of detailed drawings and specifications for the system and detailed program plans for its acquisition and deployment. Parametric cost estimates are made by first determining and costing causal relationships between physical or functional characteristics (parameters) of past systems, and then comparing the parameters of a new system to these past relationships for possible extrapolation or interpolation of new-system costs. Statistical analysis of historical costs and parametric variables is commonly used to develop parametric cost-estimating relationships for systems of particular functional types. Cost estimation by analogy derives costs of new programs and products from data on past costs of similar programs or

products. Frequently, this technique involves estimation of the incremental or marginal cost associated with product improvement and production. Finally, subjective or judgmental cost estimation is used whenever data are not available on similar programs or products and when large areas of undefined effort are involved. This kind of estimation, often referred to as "engineering judgment," attempts to synthesize the program and cost-estimating experience of experts and to apply this insight to new, undefined programs. Each of these estimating tools can be applied with varying degrees of success during the electronic system life cycle as summarized in Table IV-8.

2. Application of Cost-Estimating Methodologies

The successful application of the general methodologies described above depends critically upon the position of the program or product in the acquisition process. While expert subjective cost estimates based upon past experience can be used throughout the product acquisition cycle, other cost-estimating techniques are dependent upon information developed as a component, system, or weapon proceeds from advanced development to production. The engineering technique of cost estimation is of limited value until procedural details of a development program can be specified and general concepts and characteristics of the equipment can be identified. Parametric and analog cost estimates depend heavily upon identification of characteristic physical or functional performance variables and the general technology (e.g., discrete semiconductor, LSI, digital, analog, electromechanical) for a new system. Often, this information is not realistically known until preproduction prototypes have been built. Premature application of these techniques can be heavily biased by previous levels of technology and may fail to account for rapid technological advances, as well as discrepancies between planned and achieved performance. The rapid technological change in electronics, relative to other equipments, makes this factor exceptionally important for electronics cost estimation.

Even when a new product reaches the production stage, considerable uncertainty still remains about the eventual outcome of the production

TABLE IV-8. TECHNIQUES FOR ELECTRONICS COST ESTIMATING

ESTIMATING TECHNIQUE	APPLICATION	ADVANTAGES	DISADVANTAGES
Engineering Estimates	Reprocurement	Most detailed technique	Requires detailed program and product definition.
	Production	Best inherent accuracy	Time consuming and may be expensive
	Development	Provides best estimating base for future program change estimates	Subject to engineering bias May overlook system integration costs
Parametric Estimates	Production	Application is simple and low cost	Requires parametric cost relationships to be established
	Development Planning	Statistical data base can provide expected values and prediction intervals Can be used for equipment or systems prior to detail design or program planning	Limited frequently to specific subsystems or functional hardware of systems Depends on quantity and quality of the data base Limited by data and number of independent variables
Equipment/Subsystem Analogy Estimates	Reprocurement Production Development	Relatively simple Low cost Emphasizes incremental program and product changes	Require analogous product and program data Limited to stable technology Narrow range of electronic applications
	Program Planning	Good accuracy for similar systems	May be limited to systems and equipment built by the same firm
Expert Opinion	All program phases	Available when there are insufficient data, parametric cost relationships, or program/product definition	Subject to bias Increased product or program complexity can degrade estimates Estimate substantiation is not quantifiable

program, as well as the operational performance of the product. Investigations made during the present study indicate that the cost uncertainties of production are strongly coupled to the operational performance required. Engineering changes and retrofit costs can be major contributors to production-cost growth.

Each phase of the acquisition process, therefore, contains many unknowns that impact upon the accuracy of cost estimation. As shown in Table IV-9, these unknowns are reduced as the acquisition process proceeds into production, but, even at procurement, several major areas of uncertainty that influence cost-estimating ability continue to exist.

3. Problem Areas in Cost Estimation

Key problem areas that constrain attempts to improve the accuracy of electronics cost estimates are electronics-cost data acquisition, cost-estimating methodologies, and rapid technological change. Other important influencing factors, such as economic and business base-cost projections, must also be analyzed in an effort to improve the resultant cost estimate. Improvements in these areas can help to reduce electronics cost-estimating uncertainties but will not eliminate them.

The study found that one of the most common problems of electronics cost estimation is the lack of accurate cost and performance data on previously developed and deployed systems, subsystems, and equipments. In the categories of research and development and procurement, the data on a wide range of electronics are unavailable to analysts because of the subsystem or integral nature of the electronics. Separate units of military electronic equipment designated by AN/nomenclature are frequently developed and procured by prime contracts; therefore, contract cost data should be available for historical analysis. However, study after study has discovered that historical contract records are frequently incomplete, inconsistent, and lack detailed data on equipment costs during the production phase.⁴³ Research and development costs are also difficult to obtain, even when contractual information is available, because electronics development programs typically spawn a number of end-items. Apportionment of development efforts and costs to one specific electronic product is often a matter of judgment or arbitrary allocation. Another problem that

TABLE IV-9. COST-ESTIMATING "KNOWNs" AND "UNKNOWNs" AT VARIOUS STAGES IN THE ACQUISITION PROCESS, ESTIMATING TECHNIQUES, AND PROBABLE ACCURACY

	ESTIMATING "KNOWNs"	ESTIMATING "UNKNOWNs"	ESTIMATING TECHNIQUES	PROBABLE ACCURACY OF ESTIMATE
Cost estimating at program initiation	<ol style="list-style-type: none"> 1. Conceptual configuration 2. Analog description of system 3. General approach to concept verification 	<ol style="list-style-type: none"> 1. Ultimate program or product description 2. Ultimate performance 3. Ultimate technological problem areas (unknown "unknowns") 4. Ultimate producibility 5. Development program plan 6. Production quantities or rate 7. Reliability or maintainability 8. Future economic conditions 9. Future business conditions 	<ol style="list-style-type: none"> 1. Analog estimates 2. Parametric estimate 3. Expert opinion 	<ol style="list-style-type: none"> 1. Expected under-estimate of 100 percent with a standard deviation of 100 percent
Cost estimating at DSARC II	<ol style="list-style-type: none"> 1. Prototype configuration 2. Specified performance "envelope" 3. Specified development schedule 4. Areas of anticipated risk (known "unknowns") 5. Estimated development program plan 	<ol style="list-style-type: none"> 1. Performance deviations technical, reliability, maintainability 2. Test success 3. Technology growth rate 4. Engineering changes 5. Economic changes 6. Business base changes 7. Schedule changes 8. Producibility 9. Unknown "unknowns" 	<ol style="list-style-type: none"> 1. Engineering estimates 2. Analogy estimates 3. Parametric estimates 4. Expert opinion 	<ol style="list-style-type: none"> 1. Expected under-estimate of 80% with a standard deviation of 100 percent
Cost estimating at DSARC III	<ol style="list-style-type: none"> 1. System configuration 2. Production process 3. Production prototype reliability and maintainability 	<ol style="list-style-type: none"> 1. Economic changes 2. Business base changes 3. Product configuration changes 4. Future production rate 5. Producibility in high rate production 6. Operational reliability and maintainability 7. True cost of operations 	<ol style="list-style-type: none"> 1. Engineering estimates 2. Analogy estimates 3. CER's and LCC models 4. Expert opinion 	<ol style="list-style-type: none"> 1. Expected under-estimate of 50 percent with a standard deviation of 35 percent 2. Operating and maintenance cost
Cost estimating at reprourement	<ol style="list-style-type: none"> 1. Equipment/system configuration 2. Production process 3. Procurement cost of previous buy 4. Reported reliability and maintainability 	<ol style="list-style-type: none"> 1. Economic changes (direct and indirect costs) 2. Business base changes (indirect costs) 3. Ability of competitors to produce an acceptable product 4. Production rate and quantity changes 5. True cost of operations (equipment and personnel) 6. Support changes 	<ol style="list-style-type: none"> 1. Engineering estimates (production) 2. Analogy estimates (production and operation) 3. Expert opinion (business and economic forecasting) 	<ol style="list-style-type: none"> 1. Production cost -- expected under-estimate of 25 percent with a standard deviation of 7 percent 2. Operating and maintenance cost

enters into analysis of procurement and development contract efforts is the fact that the actual cost can be obtained only from contracts that are cost-reimbursable. Fixed-price contracts reflect contractor price but not incurred cost. Such data can be misleading as well as inaccurate for cost-data analysis.

When electronics is deployed in the field, the cost of operations and maintenance activities must be based upon data furnished by the reporting systems of the Services. However, these systems are presently designed to record operational maintenance activities (or performance). Except for work accomplished at the depot level, they do not attempt to estimate actual costs incurred during maintenance of electronic components. To date, the total operations and maintenance cost, which includes cost of organizational and intermediate maintenance, is not available from Service accounting systems. A key part of the life-cycle costs incurred by electronics must, therefore, be estimated rather than retrieved from historical data.

A second major problem area contributing to electronics cost uncertainty is the methodology available to the estimator. Cost-estimating methodology must have good cost data on previous systems and a credible relationship that relates past costs to future program or product variables. Notwithstanding the poor condition of the data base as discussed above, the state of the art of cost-estimation methodology also contains independent weaknesses. Because of the rapid advance of electronic technology, there has yet been little parametric correlation between electronic product performance and cost.* Independent parametric cost estimates (IPCEs), represented as an important DOD tool for assessing contractor and program-office estimates, have been weak in the electronics area because of the paucity of valid parametric cost relationships and because of rapidly changing technology and costs. Contractors have attempted to construct parametric relationships for their products with only marginal success.⁴⁴ When they need accurate cost estimates, they

*The successful correlations between cost and performance (or physical characteristics) have been so sparse that they have become isolated examples. The principal successes are limited to sonars, inertial navigation platforms, selected radars, and military spacecraft.

unanimously turn to detailed engineering-cost estimates constructed from cost-activity experience on previous programs. Applying this technique, the contractors are in reality applying parametric costing at a greater level of detail and building up the total estimate from component parts. Their success in using this technique has not been widely documented, but contractors are uniformly convinced that the engineering estimate is the most accurate.

Use of industrial engineering estimating techniques has been extended to DOD in a limited way by the RCA Corporation through the contractual use of a proprietary computerized model, PRICE, which calculates development and production costs from several (more than 50) product physical and functional variables and program schedules. This system contains a terminal-operated capability for simulating detailed engineering estimates and producing diagnostic cost-sensitivity analyses. Investigations of this technique indicate that, despite the limitations in software estimation and RCA-oriented costing procedures, the PRICE system is an extremely useful tool for independent estimate generation based upon an extensive industrial data base.

In almost every case investigated, various cost-estimating methodologies for electronics have not stood the test of empirical verification by long-run program-cost experience. Thus, there is little indication that the electronics cost-estimating methodology developed in recent years has improved the DOD ability to predict electronics costs. In terms of life-cycle cost estimates including operations and maintenance costs, the lack of actual operational-cost data has effectively prevented a meaningful test of the various detailed and complex models. The universal reliance of these models upon mean-time-between-failures (MTBF) and mean-time-to-repair (MTTR) characteristics of the equipment is also noted. Failure to verify or confirm the costs predicted by the models has affected their utility so that application of the models to comparative analyses or cost/performance tradeoffs is believed to be marginal for most types of electronics applications.

Other problems abound in the area of electronics cost estimation. Very little effort has been sponsored to improve DOD's ability to estimate

the impacts of schedule changes and of rapidly advancing electronics technology program cost, the effects of competition and the influence of micro- and macro-economic variables on electronics acquisition, and the impact of a policy of voluntary armed forces on electronics maintenance costs. Costs of computer programming and other software design and development efforts have not been analyzed; contract estimates differing by an order of magnitude continue to be submitted for similar software tasks. Finally, only recently have cost estimates of electronic weapons systems and equipment been made that illustrate the confidence in or the prediction intervals of the estimates. These problem areas accompany estimates of the expected value of electronics and, perhaps even more important, assessment of the estimates as predictors based upon the input variables.

3. Findings and Recommendations

a. Findings

- A variety of cost-estimating tools and techniques are available for electronics; however, their development and application to electronics have been restricted because of an inability to obtain appropriate input data.
- Parametric estimates for electronics have been generally inadequate to predict future program or product costs accurately. This is attributed to failure to establish cost/performance causal relationships for the equipment and to rapidly changing technologies and associated costs.
- Computer-based models of detailed cost-estimating procedures at the lowest work level (such as the RCA PRICE model) have been used successfully by industry for reducing estimating uncertainty. DOD use of these estimating techniques through contractor or in-house model development represents a promising approach to improved cost estimation.
- The continued development of electronics cost-estimating methodologies could be enhanced by establishing repositories for electronics contract data.

- While improvements in variable cost estimates for products and programs will reduce estimating uncertainty a great deal, about 30 percent of the documented program-cost overruns have been attributed to economic factors. These areas of cost uncertainty (which indirectly affect other areas) must be addressed by both Government and industry if big improvements in electronics cost estimation are to be expected.
- Improvements in estimates of life-cycle or ownership costs are being retarded because of the lack of a universal cost-element definition and the lack of knowledge of the direct and indirect operating costs to the Government that are appropriately associated with specific electronic equipments, subsystems, and systems. Identification and quantification of these elements are too often delegated to competing contractors who are motivated to select those factors and cost elements that tend to show their products in the most favorable light.

b. Recommendations. The above findings lead to a number of policy recommendations for DOD in the area of electronics acquisition and operation. The policies recommended below are designed to yield additional information on and better estimates of electronics cost during the product life cycle. However, to be applied with maximum benefit, they must be implemented at the lowest and most effective decisionmaking level within DOD and used for program/product tradeoffs, beginning with DSARC I.

- DOD should strengthen its ability to independently estimate electronics acquisition costs. DOD can begin this task by:
 - Continuing efforts to develop parametric cost-estimating relationships for major electronic systems containing a limited number of cost-related variables.
 - Developing an in-house or independent-contractor capability to construct detailed engineering estimates for electronic equipment. To establish such a capability will require coordination of Service laboratories, procurement commands, project offices, and contractor support.

- DOD should standardize life-cycle cost-estimating for specific types of electronics and should provide all Service cost factors needed by the models to derive operations and maintenance costs that are comparable and consistent.

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APPENDIX A

ELECTRONICS-X TASK ORDER



DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

1400 WILSON BOULEVARD
ARLINGTON, VIRGINIA 22209



TASK ORDER FOR WORK TO BE PERFORMED

BY

INSTITUTE FOR DEFENSE ANALYSES

TASK ORDER T-97

DATE 21 February 1973

You are hereby requested to undertake the following task:

1. Title: Electronics-X

2. Background: Sharply rising costs of electronic systems and unsatisfactory field reliability mandate an initiative by DDR&E to lower the costs of military electronics equipment and improve its field reliability/maintainability, while still attaining acceptable performance and schedules. In furtherance of these objectives, DDR&E plans to support, with several contractors, a number of study efforts related to cost reduction and reliability improvement. It is intended that these efforts will be monitored and the results integrated by IDA and augmented as necessary to provide a base of information and tentative recommendations for consideration by a Summer Study Group to be convened by IDA. The depth of the treatment of several of the areas in this overall program will depend on the timely availability of the results of these other studies and on the level of effort which can be made available to the IDA studies.

3. Task Objective: The overall program objectives are to identify and evaluate current and alternative DoD and industry policies, procedures and practices in development, production and operational support which most significantly influence acquisition and life cycle costs and field reliability and to recommend changes and improvements to reduce and control such costs and improve reliability. In furtherance of these objectives, IDA will

a. Monitor the severa' DDR&E-supported study programs, and provide guidance and coordination of the efforts, to the extent feasible within contractual constraints, to assure that the studies address critical issues and consider potential remedial actions.

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TASK ORDER T-97

Electronics-X

b. Perform supporting studies to

(1) Determine the high pay-off areas -- that is, those classes of systems or elements of life-cycle cost for which changes in existing policies and procedures would be of greatest value.

(2) Examine comparable equipment acquisition cases with a view toward discovering the pathological elements in those acquisitions whose cost is determined to be excessive or whose reliability is determined to be inadequate.

(3) Evaluate potential remedial actions and alternative policies, procedures and practices aimed at reducing cost and increasing reliability of military electronics equipment.

c. Integrate the output of the many study efforts and arrive at tentative conclusions and recommendations as to policies, procedures and practices which could implement attainment of reduced cost and improved maintainability/reliability. Arrange a coordinated briefing, to the members of a Summer Study Group, on the results of the study efforts and the tentative conclusions and recommendations drawn therefrom.

d. Organize and convene a Summer Study Group composed of senior DoD and industrial personnel to review the results of the prior effort and arrive at overall conclusions and recommendations.

e. Brief DoD officials on the findings of the Summer Study Group.

f. Edit and deliver the final report of the Group.

4. Scope: The technical monitoring of the DDR&E-sponsored study efforts will include recommendations to DDR&E for redirection when appropriate, but will not include direction, supervision, contract negotiation or contract management. The breadth of coverage in this study of the various categories and types of electronic equipment and systems used by the DoD will be determined by the overall support provided to the effort, including contracted DDR&E studies and augmentation of the IDA overall study integration and coordination team. (See "Level of Effort")

TASK ORDER T-97

Electronics-X

5. Schedule: Work shall commence upon the acceptance of this task, and shall be completed by the end of October 1973.

Briefing of DoD officials on the findings of the Electronics-X Study shall be accomplished about September 1, 1973. The final report shall be delivered about October 1, 1973.

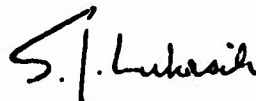
6. Level of Effort: Costs for this study will not exceed \$480,000 in FY 1973 and \$320,000 in FY 1974. Additional effort will be provided by DDR&E in the form of full and part time study participants from the DoD and other contractors.

7. Technical Cognizance: Assistant Director (Electronics), ODDR&E.

8. Distribution and Control: Assistant Director (Electronics), ODDR&E.


9. Specific Instructions and Limitations: To guide this study there will be established an OSD Steering Group chaired by the Assistant Director (Electronics), ODDR&E. Close liaison will be maintained between the Electronics-X project director and the OSD Steering Group during the work period.

A "need-to-know" is hereby established in connection with this task and access to information in the field of this task is authorized for participating personnel and such supervisory and advisory personnel as are deemed necessary.



S. J. Lukasik
Director

ACCEPTED:


Alexander H. Flax
President, IDA

DATE: January 12, 1973

APPENDIX B

ESTIMATES OF DOD ELECTRONICS COSTS

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A. INTRODUCTION

A primary indicator of the importance of electronics is the percentage of the annual defense budget allocated to electronic equipment, subsystems, and systems. The contribution of electronics to the total defense acquisition and operating budget is also vital information if the effects of continued budget constraints are to be assessed and areas of financial leverage identified.

Unfortunately, Government expenditures for military electronics are not readily visible in either the budgets or the accounting records at the Office of the Secretary of Defense (OSD) level. For research and development expenditures, electronics is contained within program elements that are either technology-oriented or product-oriented. Electronics expenditures are frequently a major part of these programs but cannot be identified as an explicit percentage or dollar amount. This difficulty is also encountered frequently in the procurement budget, where the level of financial detail does not permit identification and measurement of electronic subsystem costs. Finally, operations and maintenance costs for electronics have been difficult to identify at the OSD level because budgeting detail is insufficient to identify electronics allocations, and Service accounting systems have not reported full costs of electronics operations and maintenance.*

Because of the difficulties associated with obtaining a detailed "bottom-up" estimate of electronics expenditures and the large uncertainties associated with estimating the portion of weapons systems cost attributable to electronic subsystems, a budgetary estimate using OASD (Comptroller) and other data was made to indicate the probable magnitude of actual electronics RDT&E, procurement, and support costs. The DOD budget for 1974, outlined in Table B-1, was selected for analysis.

*The military Services have been pursuing the accounting of maintenance costs by equipment identification. However, these programs are still in the initial stages of implementation and have yet to be validated.

TABLE B-1. FY 1974 DOD BUDGET

<u>Budget Category</u>	<u>Estimated Outlay, billions</u>	<u>Percentage of Total DOD Budget</u>
Research and Development	\$ 8.1	10%
Procurement	16.5	20
Operations and Maintenance	21.7	27
Military Construction	1.7	2
Military Personnel	22.5	28
Retired Military Personnel	4.7	6
Allowances and Other Outlays	<u>5.9</u>	<u>7</u>
Total	\$81.1	100%

An estimate of the Government "market" in electronics is compiled annually by the Electronic Industries Association (EIA). This estimate is based upon a survey of the EIA member companies and consists of their estimates of future Government spending.* Where Government data do not provide sufficient detail or cost allocation information, estimates or factors derived from the EIA forecast were incorporated into the analyses.

B. DOD EXPENDITURES FOR ELECTRONICS RESEARCH AND DEVELOPMENT

Expenditures for electronics research and development can be estimated by a methodology which separates the industry share of the expenditures and estimates the electronics content of the contractual effort separately from the Government in-house R&D. Once total electronics expenditures are estimated for each sector (Government and industry), estimates of direct and indirect costs associated with each sector can be made by using industry averages and Government program-element analyses.

*The Government "market" is defined by the EIA as "that part of the budget which EIA member companies can pursue as business opportunities."

A summary of contract data for the 4 fiscal years 1969-1972 has been obtained from OSD (Comptroller) and is shown in Table B-2.

TABLE B-2. DOD EXPENDITURES FOR
RDT&E CONTRACTED TO INDUSTRY

(dollars in millions)

Item	Fiscal Year			
	1969	1970	1971	1972
Total DOD RDT&E	\$7,457	\$7,166	\$7,303	\$7,780
Total DOD Contracted RDT&E ^a	\$6,013	\$5,466	\$5,538	\$5,844
Percentage of RDT&E Contracted	80.6%	76.3%	75.8%	75.1%

^aSource: Ref. 1.

According to these data, an average of 76.9 percent of total RDT&E expenditures have been contracted to industry. If the downward trend of the contractor share is accounted for, the least-squares fit of the data yields values of 72.7 percent for FY 1973 and 71.0 percent for FY 1974 for the contracted portion of the budget. For FY 1974, with projected outlays of \$8.1 billion, these percentage estimates indicate that the contracted RDT&E will range between \$5.8 billion and \$6.2 billion.

The amount of electronics contained in the \$6.0 billion of contract RDT&E can be estimated by examining the contract expenditures by Federal Supply Classification groups. It was found that the four groups that contain the bulk of all electronics RDT&E are: aircraft equipment and supplies (excluding airframes, engines, and related parts), missile and space systems, ships, and electronic and communication equipment. Within these groups it was estimated that roughly all of the expenditures on aircraft components, 75 percent of the expenditures on missile and space systems, 20 percent of the expenditures

on ships, and all of the expenditures on electronic and communication equipment were for electronics.* The 4-year summary of these groups and their estimated electronics content is shown in Table B-3.

TABLE B-3. ELECTRONICS R&D CONTRACT EXPENDITURES

(current dollars in millions)

<u>Item</u>	<u>Fiscal Year</u>			
	<u>1969</u>	<u>1970</u>	<u>1971</u>	<u>1972</u>
Aircraft Equipment and Accessories	\$ 94.8	\$ 36.4	\$ 86.4	\$ 195.5
Missiles and Space	2053.7	1688.9	1174.7	1529.7
Ships	28.1	21.5	15.6	18.9
Electronics and Communications	911.9	953.7	1074.0	1163.4
Total Electronics Contract R&D	\$3088.5	\$2700.5	\$2350.7	\$2907.5
Electronics Contract Expenditures as Percentage of Total Contract R&D	51.4%	49.4%	42.4%	49.8%

The average electronics content of the 4-year data presented in Table B-3 amounts to 48.3 percent of all contracted R&D. For FY 1974 expenditures of \$6 billion, the electronics contract expenditures based upon previous year estimates are estimated to be \$2.9 billion. The distribution of this estimate between R&D categories is shown in Table B-4.

* Derivation of these percentage estimates is discussed in Section E of this appendix.

TABLE B-4. R&D FUNDING TO CONTRACTORS, FY 1974

<u>Contract RDT&E Category</u>	<u>Dollar Amount, billions</u>	<u>Percentage of Total Contract Electronics R&D</u>	<u>Percentage Total DOD R&D</u>
Electronics Research, Exploratory Development, and Management Support	\$0.3	10%	4%
Electronics Advanced, Engineering, and Operational Development:	2.6	90	32
Aircraft Electronics	\$0.4	16%	
Missile and Space Electronics	1.1	42	
Ship Electronics	0.1	4	
Communications	1.0	38	
Total Contract Electronics R&D	\$2.9	100%	36%

The Government portion of the total expenditures for electronics research and development was estimated by applying the percentage distributions for all RDT&E funds as estimated by the Electronic Industries Association (EIA) for FY 1973 in Table B-5.²

TABLE B-5. DISTRIBUTION OF FY 1973 RDT&E EXPENDITURES^a

<u>RDT&E Expenditure to:</u>	<u>Dollar Amount, millions</u>	<u>Percentage Distribution</u>
Industry	\$5642.2	66.0%
Government In-House	2445.9	28.6
Federal Contract Research Centers	214.7	2.5
Universities	199.0	2.3
Emergency Fund	50.0	0.6

^aSource: Ref. 2.

Based upon previous estimates for a contracted electronics effort of \$2.9 billion, the EIA estimate of 28.6 percent of total expenditures incurred by the Government yields a Government in-house expenditure for electronics of \$1.2 billion. Within RDT&E budget categories, the distribution is estimated by using similar ratio relationships as shown in Table B-6. Table B-7 summarizes the combined R&D budget allocation estimate for electronics.

TABLE B-6. GOVERNMENT IN-HOUSE R&D FUNDING, FY 1974

<u>Budget Category</u>	<u>Dollar Amount, billions</u>	<u>Percentage of Total Government Electronics R&D</u>	<u>Percentage of Total DOD R&D</u>
Electronics Research, Exploratory Development, and Management	\$0.2	17%	3%
Electronics Advanced, Engineering, and Operational Development	1.0	83	12
Total In-House Electronics R&D	\$1.2	100%	15%

TABLE B-7. SUMMARY OF DOD FY 1974 R&D BUDGET ALLOCATION

<u>Budget Category</u>	<u>Dollar Amount, billions</u>	<u>Percentage of Total Electronics R&D</u>	<u>Percentage of Total DOD R&D</u>
Total DOD Electronics Research, Exploratory Development, and Support	\$0.5	12%	7%
Total DOD Electronics Advanced, Engineering, and Operational Develop- ment	3.6	88	44
Total DOD Elec- tronics R&D	\$4.1	100%	51%

As shown by the summary tables, it is estimated that approximately \$4.1 billion or 51 percent of the total DOD budget for research and development in FY 1974 will be for electronics. Almost 90 percent of the electronics expenditures will be for advanced, engineering, or operational development programs with roughly 70 percent of the work under contract. The largest sources of electronics R&D contract expenditures are missiles, space, and communication equipment. Aircraft and ship electronics account for another 20 percent of total contract amounts. Electronic equipment, subsystem, and system research and development therefore represent a substantial and important part of the DOD R&D budget.

C. DOD EXPENDITURES FOR ELECTRONICS PROCUREMENT

Estimates of electronics procurement expenditures were derived by using methodology similar to that employed for estimating research and development expenditures. Industry contract estimates were constructed by using averages of estimated electronics contract amounts for previous years. Government electronics expenditures were based upon estimates of the electronics content of procurement operations program elements. The sum of industry contracts and Government support result in the total electronics procurement estimate.

The electronics industry share of the total procurement expenditures, estimated to be \$16.5 billion for FY 1974, was estimated by evaluating contract distributions by Federal Supply Classification for fiscal years 1969 through 1972. As shown in Table B-8, the estimated electronics content over the 4-year period was 30.8 percent of all contract amounts in procurement. The trend during the most recent 3-year period indicates a greater percentage than the average is likely for projections of 1974.* Based upon this trend,

* It should be noted that the contract procurement represents approximately 92 percent of the total procurement budget, which amounts to \$15.2 billion for FY 1974.

a factor of 34 percent of contract procurement, or a total of \$5.1 billion, was estimated for FY 1974. The total and projected electronics contract distribution by Federal Supply Classification is shown in Table B-9.

TABLE B-8. DOD PROCUREMENT OF ELECTRONIC SUPPLIES
AND EQUIPMENT

(current dollars in millions)

Federal Supply Classification Code	Description	Fiscal Year			
		1969	1970	1971	1972
12	Fire-Control Equipment ^a	\$ 201.3	\$ 103.6	\$ 157.6	\$ 157.5
14	Guided Missiles ^b	2,475.5	1,515.5	1,772.2	2,267.5
15	Aircraft and Airframes ^c	1,172.4	1,027.3	990.6	1,361.1
16	Aircraft Components	522.1	339.8	255.4	248.1
58	Communication Equipment	1,927.5	1,594.9	1,397.5	1,825.2
59	Power & Distribution Equipment	446.7	309.1	265.8	306.7
66	Instruments	<u>531.7</u>	<u>472.7</u>	<u>395.5</u>	<u>473.3</u>
	Total DOD Electronics Procurement	\$7,279.2	\$5,362.9	\$5,234.6	\$6,639.8
	Total DOD Procurement Outlays	\$22,845.7	18,585.5	17,509.4	20,265.1
	Electronics Percentage of All DOD Contract Procurement	31.9%	28.9%	29.9%	32.7%

^aIncludes shipboard installation of fire-control equipment.

^bEstimated at 75 percent of total contract amount.

^cEstimated at 30 percent of total contract amount.

TABLE B-9. PROCUREMENT FUNDING TO CONTRACTORS, FY 1974

Category of Weapon System or Equipment	Electronics Procurement, billions	Percentage of Total Contract Procurement	Percentage of	
			Total DOD Electronics Procurement	Percentage of Total DOD Procurement
Fire-Control Equipment ^a	\$0.2	4%	3%	1%
Missiles & Space Vehicles	1.7	33	29	10
Aircraft Equipment	1.2	24	21	7
Electronic Component	0.2	4	4	1
Communication Equipment ^a	1.3	25	22	8
Electronic Instruments	0.4	8	7	4
Other	<u>0.1</u>	<u>2</u>	<u>2</u>	<u>1</u>
Total Electronics Procurement	\$5.1	100%	88%	31%

^aThese categories include approximately \$0.8 billion in shipboard equipment.

Government in-house expenditures for electronics procurement were estimated at \$700 million or approximately 50 percent of total in-house procurement expenditures. While the precise allocation of these costs has not been investigated, the majority of electronics procurement support costs are believed to be in the large procurement operations associated with the AECOM, AFSC, NAVAIR, and NAVELEX organizations. Procurement support, funded under the operations and maintenance budget category, could logically be assigned to this category as well. These expenditures total approximately \$0.5 billion annually out of a total Program VII general supply budget of \$2 billion.

A summary of estimated FY 1974 electronics procurement is shown in Table B-10. These estimates show that approximately \$5.8 billion or 35 percent of all DOD procurement outlays for FY 1974 are for electronics. Most of the funds are expended by contractors, as expected. Expenditures for missiles, space, aircraft, and communication equipment (including shipboard equipment) represent roughly 70 percent of all electronics procurement outlays, for a total contract amount of \$4.2 billion. The major part of these expenditures is for equipment and subsystems that are integrated with and installed in complete aircraft, missile, or space systems.

TABLE B-10. SUMMARY OF DOD FY 1974 ELECTRONICS
PROCUREMENT BUDGET ALLOCATION

<u>Budget Category</u>	<u>Estimated Electronics Expenditures, billions</u>	<u>Percentage of Total Electronics Procurement</u>	<u>Percentage of Total DOD Procurement</u>
Industry Contracts	\$5.1	88%	31%
Government In-House Procurement Support	0.7	12%	4%
Total DOD Electronics Procurement	\$5.8	100%	35%

D. DOD EXPENDITURES FOR ELECTRONICS SUPPORT

The cost of electronics support has been one of the most difficult areas to estimate accurately because of the large quantity and many types of equipment, subsystems, and systems in the field and the difficulties encountered in apportioning direct and indirect costs associated with maintenance costs of specific equipments. Since only a gross examination was attempted during this study, the resulting estimates are acknowledged to be imprecise.

The term "electronics support" is defined here as including those elements of the Operations and Maintenance (O&M) and Military

Personnel (MP) budget categories that relate to logistic support and maintenance of electronic equipment. The cost of actually operating electronic equipment is specifically excluded from these estimates. Four methods of arriving at estimated annual support costs are treated below.

Method 1. Bottom-Up Estimate from Budget Data

Within the OEM budget category are, among other items, prime contract awards for maintenance services. These are enumerated in Table B-11 for the fiscal years 1969-1972; for FY 1972 the total was \$377 million.

TABLE B-11. ELECTRONICS CONTRACT EXPENDITURES FOR
MAINTENANCE SERVICES

(current dollars in millions)

Description	Fiscal Year			
	1969	1970	1971	1972
Aircraft Electronics Maintenance	\$ 95.2	\$ 93.3	\$ 86.7	\$105.1
Missile Electronics Maintenance	37.6	21.8	18.2	23.5
Communications Maintenance	96.4	76.8	79.9	93.2
Communications Modifications	57.5	68.6	72.9	91.9
Electronics Technical Representatives, Aircraft	6.8	11.4	7.3	8.9
Technical Representatives, Missiles	24.3	6.9	9.4	9.9
Technical Representatives, Communications	76.4	59.9	52.3	44.1
Total Electronics Contract Maintenance Services	\$394.2	\$338.7	\$326.7	\$376.6

A second element of the O&M budget that is directly related to electronics support comprises the salaries of civilian employees at military electronics maintenance depots. The number of employees³ is 18,601, and their average salary, based on salaries at the Sacramento Army Depot, is \$12,500 plus 14 percent for retirement and fringe benefits. The total for this item is \$266 million.

A third element of the O&M budget category represents an indirect cost of electronics maintenance: that fraction of administrative, central supply and maintenance, and training and medical costs that is associated with support of the military personnel working in electronics maintenance. The number of military personnel with electronics maintenance military occupational specialties (MOSs) assigned to electronics maintenance is estimated³ as 172,643 or 7.58 percent of the total average number of personnel in the armed forces in FY 1974. Applying this percentage to the specified cost elements in the O&M category yields an amount of \$792 million.

Finally, the O&M budget category includes the cost of operating the Defense Supply Agency (DSA). The electronics content of the in-use military inventory, as developed later in this appendix, is 28 percent. Applying this percentage to the DSA O&M element yields \$197 million.

Turning to military personnel costs, the first element, direct compensation and expenses, is taken as 7.58 percent of the total MPA budget category, excluding reserve pay, and is found to be \$1587 million.

The indirect electronics maintenance cost of military administrative personnel to support the electronics maintenance personnel is estimated at 7.58 percent of this MPA cost element, and yields \$35 million.

The indirect electronics maintenance cost of training and medical military personnel to support electronics maintenance personnel is estimated at 7.58 percent of this MPA cost element, or \$510 million.

Finally, based on the ratio of 1974 retirement costs to total 1974 personnel costs excluding reserves, military retirement costs are estimated at 22.5 percent of the annual military personnel costs directly or indirectly allocable to electronics maintenance; this amounts to \$479 million.

To summarize the electronics support cost estimate obtained by this approach, we find:

	<u>billions</u>
Contract maintenance (O&M)	\$0.377
Depot civilians, including fringe benefits and retirement (O&M)	0.266
Allowable administrative, central supply, training and medical (O&M)	0.792
Electronics content of DSA (O&M)	0.197
Military maintenance personnel costs (MP)	1.587
Allocable military administrative costs (MP)	0.035
Allocable training and medical military personnel (MP)	0.510
Military retirement costs (Ret.)	<u>0.479</u>
	<u>\$4.243</u>

Thus, the total annual electronics support cost estimated by this method is \$4.2 billion.

In estimates such as the above, there is a strong likelihood that certain elements of support cost have been overlooked. To obtain alternative estimates, three other approaches were pursued and are described below.

Method 2. Extrapolation from Standard-Function Avionics Maintenance Costs

Arinc Research Corporation has made a careful independent estimate⁴ of the annual maintenance cost of communication, navigation, and identification (CNI) avionics for 38 commonly used Air Force equipments. The estimates are based on AFM 66-1 maintenance action records and take into account both field and depot maintenance. The

estimated cost of field maintenance included labor at \$10 per man-hour, including overhead, but excluded parts costs. The estimated depot repair costs included labor, parts, overhead, G&A, etc., averaged per depot maintenance action times the number of depot referrals observed during the sampling period. The sampling period was July 1970 to June 1971.

The operating duty factor for the equipments was assumed to be equal to that of the aircraft in which they were commonly employed, 7.0 percent. This duty factor is assumed to be not unreasonable for military electronic equipments other than those used in aircraft.

The total annual maintenance cost, weighted by inventory quantity, for these 38 equipments, was derived from the Arinc Research results as \$46 million. To this we add the cost of repair parts used in field maintenance, estimated at 5 percent of the field maintenance labor costs, which are in turn (from Arinc Research data) estimated at 86 percent of the total. The total annual maintenance cost becomes \$48 million. The investment cost for the 38 equipment types, taking into account the quantity of each, is \$341 million.

Thus, the annual maintenance cost as a fraction of investment cost is estimated at 14.14 percent.

Applying this same ratio to the current DOD-wide in-use electronics inventory of \$31.1 billion, as estimated later in this appendix, the annual support cost for military electronics is estimated as \$4.4 billion.

Method 3. Estimation from Failure Rates and Cost per Failure

The total DOD in-use avionics inventory is estimated at \$13.9 billion; the remainder of electronics is estimated at \$17.2 billion (Table B-14). From Fig. II-5, in Part II of this report, it is seen that the median rate of failures per operating hour per dollar of unit production cost is, for avionics, 7.69×10^{-7} . From the Arinc Research results previously cited, the average number of operating hours per year is 617. Thus, the yearly number of failures for the avionics

inventory is 6.595×10^6 . Two widely differing estimates of the cost per failure can be derived: from a General Electric study⁵ of airborne radars, there are 2.85 maintenance actions per failure, and the cost of each maintenance action is \$220 (without source citation) for a cost per failure of \$627. On the other hand, one can derive from the Arinc Research results a weighted average cost per failure of \$298. Assuming that one-third of avionics is as difficult to service as airborne radars, while the remainder is comparable to the CNI equipments of the Arinc Research study, the two figures can be weighted and averaged. At the average cost per failure of \$408, the annual cost of maintenance of the avionics inventory is estimated at \$2.69 billion.

The failure rate for the non-avionics inventory is lower than that for avionics. Using the very limited results from Army Area Communications System (AACOMS) equipment, a rate of 10^{-7} failures per operating hour per dollar of inventory is indicated. The number of operating hours per year is assumed to be 876, for a duty factor of 10 percent. The maintenance cost per failure is assumed to be \$225 per failure, somewhat less than that for simple avionics. From these assumptions, the annual maintenance cost for non-aircraft electronics is estimated at \$3.39 billion.

Thus, the total cost of support of the military electronics in-use inventory is estimated by this method as \$6.1 billion.

Method 4. Electronics Maintenance Costs Estimated from Total Military Maintenance Costs

The Director for Maintenance Policy, OASD(I&L), estimates total annual DOD maintenance costs as follows:

	<u>billions</u>
635,000 military maintenance personnel	\$6.0
275,000 DOD civilian and 225,000 private contractor personnel	6.0
Maintenance supplies	5.0
Transportation	1.0
Modifications and alterations	2.0
Base support	1.4
Retirement pay	1.0
Training of maintenance personnel	1.0
Reserves	0.5
Military construction	0.2
Technical representatives	<u>0.1</u>
Total	\$24.2

Technical manuals, tools, and test equipment are excluded from this estimate to avoid double counting with procurement cost.

As noted earlier, electronics constitutes an estimated 28 percent of the military in-use inventory. Assuming that electronics consumes this same fraction of the defense maintenance outlay, the annual electronic support cost is estimated at \$6.8 billion.

Average and Standard Deviation of the Four Estimates

The average of the estimates of annual electronics support cost made by the four methods is \$5.4 billion.

The standard deviation is \$1.1 billion, and indicates a large uncertainty in the result. Verification of these estimates and more precise resolution of the broader question of total electronics maintenance costs must await further development of the cost accounting systems and, perhaps equally important, a definition by consensus of exactly what costs should be identified with electronics maintenance.

E. THE CONTRIBUTION OF INDIRECT COSTS

The contribution of indirect or overhead support costs as a major portion of the total electronics budget allocation has been discussed briefly above. While there is no way to estimate precisely what the aggregate percentage of support costs is for electronics, typical relationships can serve to illustrate the importance of these costs in the total budget.

In the industrial sector, indirect costs can contribute between 50 and 80 percent of total contract costs, depending upon the nature of the contracted effort, the amount of subcontract costs contained within the contract, and the contractor's business base. Studies by Martinson and Jarrett^{6,7} both show that typical indirect cost contributions for aerospace contracts are between 60 and 70 percent of total contract costs, depending upon the amount of subcontract effort. Based upon the ranges of indirect cost contribution found by these studies, a 60 percent indirect cost share was estimated for R&D and O&M contracts, and a 66 percent share ratio was used for procurement estimates, the larger percentage reflecting the greater number of subcontracting or purchasing efforts contained within the procurement of equipments, subsystems, and complete weapon systems.

The indirect costs incurred by the Government are much more difficult to estimate because of problems in identifying and apportioning the costs to electronic systems. For research and development expenditures, a Government overhead rate of 1.4 was estimated by assuming that Program Element 6.5, Management and Support, was essentially overhead or indirect cost and by calculating the ratio of Government Program Element 6.5 costs to the balance of Government R&D expenditures. Indirect ratios for Government procurement were estimated by calculating the ratios of procurement support and central supply support. For electronics, these activities were estimated at \$0.15 billion and \$0.5 billion, respectively, for an indirect rate of approximately 200 percent. The distributions represented by the

direct and indirect allocation of the electronics budget are shown in Table B-12 and Fig. B-1.

TABLE B-12. SUMMARY OF DOD ELECTRONICS
DIRECT AND INDIRECT COST ALLOCATION

Sector and Cost Category	Research and Development		Procurement	
	Dollar Amount, billions	Percentage of Total	Dollar Amount, billions	Percentage of Total
<u>Industry</u>				
Direct	\$1.2	29%	\$1.7	29%
Indirect	1.7	42	3.4	59
<u>Government</u>				
Direct	0.5	12	0.2	3
Indirect	<u>0.7</u>	<u>17</u>	<u>0.5</u>	<u>9</u>
Total	\$4.1	100%	\$5.8	100%

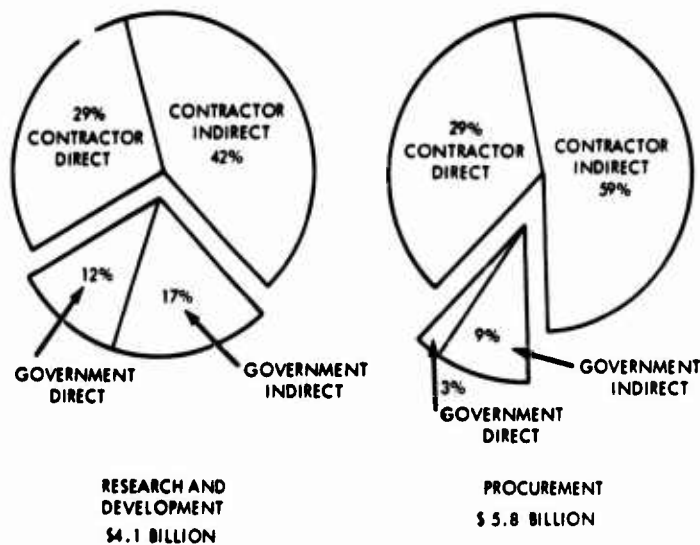


FIGURE B-1. DOD Electronics Budget Acquisition Cost Distributions

F. THE COST OF ELECTRONICS IN WEAPONS SYSTEMS

A major problem area in estimating total electronics expenditures is the determination of the electronics cost portion associated with complete weapons systems. Given the three major classes of weapons--aircraft, missiles, and ships, it is impossible to provide more than rough estimates of electronics content at the aggregate level for each class. Even within each class, groups or individual weapons systems are difficult to analyze for characteristic electronics cost content.

In the major category, aircraft, electronics content can range from 5 percent of flyaway cost, as in utility helicopters, to 30 percent, as in the F-14A. Electronic-warfare aircraft, whose primary mission is electronic, can represent considerably greater percentages of total flyaway cost. The cost of airborne electronics is obscured further by the fact that the total electronics costs must consider equipment installation, integration and test, ground support equipment, and initial spares costs, in addition to discrete equipment costs. These additional costs were analyzed for the mission avionics of 11 tactical fighters in a previous IDA study, which showed that while the mission avionics equipment represented an average of 16 percent of aircraft flyaway costs, the systems cost (including the equipment) averaged 33 percent of aircraft flyaway.⁸ Consideration of the total electronics content of these aircraft, including communications, identification, and electrical power systems, would have resulted in even greater cost percentages. Similar percentages are used by other estimators; the Navy uses a factor of 28 percent,⁹ and the Electronic Industries Association (EIA) estimates 27 percent¹⁰ of aircraft procurement is electronics. Based upon somewhat higher estimates from IDA studies, 30 percent has been adopted for the estimates contained herein.

The electronics content of missile expenditures represents greater estimating uncertainties than experienced with aircraft because of the difficulties in the identification of "missile

electronics" and the wide variety of missile systems, ranging from simple BULLPUP guided bombs to POSEIDON, MINUTEMAN, and SAFEGUARD. While all available "flyaway" cost data indicate that the electronics contained in the guidance and control portions of the missiles represents between 60 and 80 percent of the cost, total program costs, which include ground support and command and control equipment, can yield a much broader range of estimates.

EIA bases its estimate of the electronics content of missiles on a factor for aggregate electronics in missile procurement of 45 percent. On the basis of data on missile flyaway costs and electronics content, it is believed that this estimate is significantly understated and that an average apportionment of 75 percent is a better aggregate estimate. An example of tactical missile electronics content is shown in Table B-13, which substantiates the higher estimate. More detailed analyses are needed to get a better estimate that would account for all appropriate missile electronic costs.

Ship electronics, like missile electronics, can also range from low percentages to major portions of total ship costs. A significant factor in ships is the installation of ship electronics, which can cost as much as the installed equipment. The Navy estimates that 12 percent of ship construction cost and 30 percent of ship modification/support cost is electronics cost. The EIA uses an average of 23 percent of total ship procurement as the electronics cost factor, which agrees with the aggregate Navy estimates. The EIA estimates are therefore believed to be representative of the value associated with shipboard electronics.

As indicated above, the use of aggregate electronics budget factors can provide only rough approximations of the electronics budget allocation. The resulting total cost estimates are probably only accurate to within a ± 20 percent estimate bandwidth.*

*The range of estimates derived from the EIA electronics forecast is ± 14 percent.

Therefore, until a detailed program-by-program, weapon-by-weapon analysis is accomplished for the fiscal year, the aggregate estimates will have to be used, recognizing the uncertainties which exist.

TABLE B-13. TACTICAL MISSILE ELECTRONICS
CONTENT AND FLYAWAY COST^a

(dollar amounts in constant 1970 dollars)

<u>Missile</u>	<u>Average Unit Flyaway Cost</u>	<u>Unit Guidance & Control Cost</u>	<u>Electronics Content, percent</u>
BULLPUP 12-B	\$ 4,375	\$ 2,537	58%
BULLPUP 12-C	6,228	3,052	49
FALCON 4-A	9,039	8,044	89
SIDEWINDER 9-D	9,980	6,487	65
FALCON 4-F	14,117	12,140	86
SHRIKE	15,192	9,870	65 $\bar{x} = 75.4\%$
SIDEWINDER 9-C	18,286	14,810	81 $\sigma_{\bar{x}} = 12\%$
SPARROW 7-D	20,330	16,460	81
FALCON 26-A	21,113	17,315	82
SPARROW 7-E	22,022	19,160	87
Standard MR	44,319	31,020	70
Standard ER	46,462	30,650	66
SPARROW 7-F	68,898	56,500	82
TALOS	112,094	99,800	77
Standard ARM	138,291	123,000	89
PHOENIX	450,000	396,000	88
HOUNDG	609,078	400,000	66

^aData Sources: Refs. 11, 12.

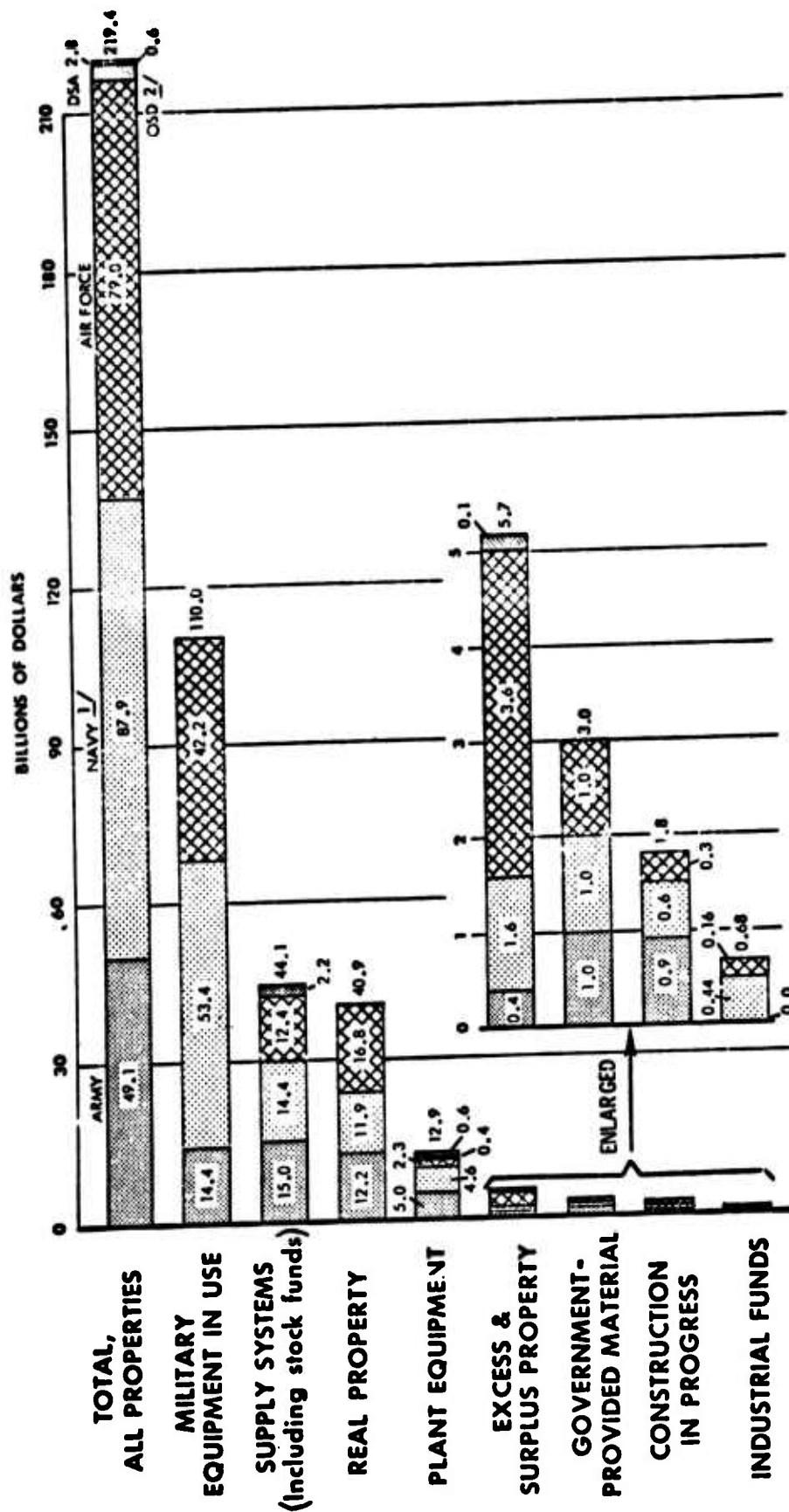
G. THE INVENTORY OF ELECTRONIC EQUIPMENT

To put the importance of electronics in final perspective, it is desirable to obtain a rough estimate of the inventory of electronic equipment as a percentage of the total DOD inventory.

The total DOD inventory of real and personal property at the end of FY 1972 was estimated at \$219.4 billion.¹³ As shown in Fig. B-2, the Navy and the Air Force manage \$167 billion, or 76 percent, of this total amount. The largest contributors to the inventory are equipment in use (50 percent), equipment in the supply system (20 percent), and real property (19 percent).

Estimates for the electronics content of the equipment in use and in the supply system were attempted by using detailed OASD (Comptroller) inventory reports from the Services. It was found that the level of aggregation provided by the inventory reporting system to the Comptroller did not identify specific categories of electronic equipment except communication equipment, and, as found in contract procurement data, the percentage of electronics contained as integral parts of complete end-item weapons systems was not visible for analysis. The estimate of electronics content therefore had to be constructed by using factors previously developed for weapon-system electronics content.

Based on the Comptroller data, the inventory of equipment in use and the estimated electronics content is compiled in Table B-14. It is thus estimated that approximately 28 percent of the inventory value of all equipment in use is electronics, and the inventory valuation totaled \$31 billion for FY 1972. The Navy and the Air Force are each estimated to have approximately \$13 billion in the electronics inventory, or about 25 percent of their total in-use inventories. The Army is estimated to have only \$5 billion in electronics inventory in use. However, this amounts to 35 percent of the total in-use inventory value.



1/ Includes Marine Corps

2/ Includes Office, Secretary of Defense and other Defense Agencies.

FIGURE B-2. DOD Real and Personal Properties by Major Type and Service, as of 30 June 1972
[Source: OASD (Comptroller)]

TABLE B-14. INVENTORY OF WEAPONS AND EQUIPMENT IN USE

(dollars in billions)

	<u>Total Inventory</u>	<u>Estimated Electronics Content, percent</u>	<u>Electronics Inventory</u>
<u>Army</u>			
Aircraft	\$ 3.1	30%	\$ 0.9
Missiles	2.6	75	1.9
Tanks and Combat Vehicles	2.9	10	0.3
Tactical & Support Vehicles	2.4	--	--
Electronic & Communication Equipment	1.7	100	1.7
Other Support Equipment	<u>2.6</u>	<u>10</u>	<u>0.3</u>
Total Army	\$ 14.4	35%	\$ 5.1
<u>Navy</u>			
Ships	\$ 34.7	20%	\$ 6.9
Service Craft	1.1	--	--
Aircraft	13.9	30	4.2
Aircraft GSE	1.1	50	0.6
Missiles	0.9	75	0.7
Ammunition	0.7	--	--
Other	<u>1.0</u>	<u>10</u>	<u>0.1</u>
Total Navy	\$ 53.4	23%	\$ 12.5
<u>Air Force</u>			
Aircraft	\$ 29.4	30%	\$ 8.8
Missiles	3.5	75	2.6
Electronic & Communication Equipment	1.8	100	1.8
Vehicles	1.0	--	--
Unit Mission Equipment	6.5	10	0.6
Other	<u>0.1</u>	<u>--</u>	<u>--</u>
Total Air Force	\$ 42.3	33%	\$ 13.8
GRAND TOTAL	<u>\$110.1</u>	<u>28%</u>	<u>\$ 31.1</u>

The electronics content of the defense inventory in the supply system (including depots) is shown in Table B-15. It is estimated that approximately 22 percent of all equipment value is electronic, yielding a total DOD electronic supply system inventory of \$9.7 billion. The Service percentages of equipment are estimated at: Army, 34 percent; Navy, 33 percent; and Air Force, 28 percent. The Defense Supply Agency accounts for the remaining 4 percent.

The total electronic equipment either in the supply system or in field use is estimated to be \$40.8 billion for FY 1972. This represents approximately 26 percent of the total DOD equipment inventory and corresponds roughly to 7 times the annual electronics procurement expenditure.

It should be recognized that the valuation of the inventory has not been analyzed in depth and that the value of the equipment on the books may be either original acquisition price or a discounted or depreciated amount. The current replacement cost of the inventory is likely to be substantially greater than inventory totals.

The total equipment inventory and its electronics content are summarized in Table B-16.

TABLE B-15. INVENTORY OF WEAPONS AND EQUIPMENT
IN SUPPLY SYSTEMS

(dollars in billions)

	<u>Total Supply Inventory</u>	<u>Estimated Electronics Content, percent</u>	<u>Electronics Supply Inventory</u>
<u>Principal Items</u>			
Weapons	\$ 0.6	--%	\$ --
Ammunition	8.9	--	--
Nonstrategic Missiles	2.4	75	1.8
Tanks, Combat Vehicles	3.0	10	0.3
Support Vehicles	0.1	5	--
Electronic & Communication Equipment	2.2	100	2.2
Other Support Equipment	1.7	10	0.2
Aircraft Engines	2.5	--	--
Shipboard Equipment	<u>0.4</u>	<u>20</u>	<u>0.1</u>
Subtotal	\$21.8	21%	\$ 4.6
<u>Secondary Items</u>			
Aircraft Components	\$ 9.9	30%	\$ 3.0
Missile Parts	1.1	75	0.8
Weapons Parts	0.9	10	0.1
Tank & Vehicle Parts	0.8	10	0.1
Ship & Submarine Parts	0.3	20	0.1
Ammunition Components	0.1	--	--
Other Repair Parts	0.6	--	--
POL	0.4	--	--
Clothing & Textiles	1.0	--	--
Subsistence	0.4	--	--
Medical-Dental Supplies	0.3	--	--
Electronic Parts	1.3	100	1.3
Other Stock Items	1.5	--	--
Shipboard Supplies	1.1	--	--
Miscellaneous	<u>2.6</u>	<u>--</u>	<u>--</u>
Subtotal	\$20.8	25%	\$ 5.1
 TOTAL SUPPLY	 <u>\$44.1</u>	 <u>22%</u>	 <u>\$ 9.7</u>

TABLE B-16. EQUIPMENT INVENTORY ESTIMATES
FOR FY 1972

(dollars in billions)

	<u>All Equipment</u>	<u>Electronics Content</u>	<u>Percentage Electronics</u>
Military Equipment in Use	\$110.1	\$31.1	28%
Military Equipment in Supply Systems	44.1	9.7	22
Total DOD Inventory	\$154.2	\$40.8	26%

H. SUMMARY OF THE ELECTRONICS COST CONTRIBUTION

The importance of electronics in the Department of Defense can be readily substantiated by a review of the estimated cost impact in both the annual budget and the existing inventory. Analysis of the existing data indicates a total estimated expenditure of \$15.3 billion in FY 1974, or 19 percent of the total DOD budget. It was also found that approximately 58 percent of the electronics expenditures are ultimately consumed by industrial firms under contract and that indirect or overhead portions of the expenditures roughly represent \$2 out of every \$3 spent. The electronics in the inventory was estimated at 26 percent or \$41 billion of the \$154 billion total DOD equipment inventory. The electronic equipment in use amounts to about \$31.1 billion and requires about \$5.4 billion, or 17 percent of investment, annually for support.

REFERENCES FOR APPENDIX B

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12. Department of the Air Force, Office of the Comptroller, T.O. 00-25-30, 30 June 1970.

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APPENDIX C

EXAMPLES OF THE FUNCTIONING OF THE REQUIREMENTS AND ACQUISITION DECISION PROCESSES

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A. MARK II AVIONICS FOR F-111 AIRCRAFT¹

Table C-1 shows the information important to this investigation. There was a difference of opinion on the requirement. Many in the Service R&D senior headquarters staff believed that with modest changes and additions to the existing system, well within the state of the art, it would be possible to achieve the attack avionics improvements that would be useful and necessary, and to add a relatively modest air-to-air capability. However, requirements and technical staffs and the aspiring avionics contractors pressed for an integrated system with a centralized digital processor that was later found to be pressing the state of the art. Key components of the integrated display had barely been demonstrated in the laboratory. The Secretary of Defense decided in favor of the advanced system. Later reviews did not lead to a decision to reduce performance specifications when it was found that costs were becoming excessive. Ultimately, the specifications for the display did have to be changed to permit it to function at all.

B. C-5A NAVIGATION SUBSYSTEM²

The essential data are given in Table C-2. Again, this case illustrates the impact of a requirement for extreme performance. As the requirement was originally written, the \$30 million to \$50 million C-5A aircraft would have been capable of entering a rough, unattended airfield, and it would have required an advanced stellar-inertial navigation system to achieve the necessary accuracy without ground-based navigation aids. When this requirement was questioned by the R&D senior headquarters staff, it was decided that the C-5A could not be used that way, and the terminal navigation performance requirement was reduced. It remained stringent enough, however, to require the development of new technology (floating-ball gyro) for the inertial navigation system (INS), at a great cost increase. While the cost growth of the INS was anticipated well in advance, the Government could not intervene, because this would have incurred the penalties of disrupting a fixed-price contract with the prime

TABLE C-1. MARK II AVIONICS FOR F-111

Original Package in F-111A	Original Concept of Improvements	Final Requirement	Cost Growth	
			Estimate	Ultimate
<ul style="list-style-type: none"> • Ground-mapping, weapon-delivery, terrain-avoidance radar (15 mi) • Standard radar display • Inertial navigation with analog computer (2 nmi/hr) • Standard bombsight; no continuously computed impact point (analog computer) 	<ul style="list-style-type: none"> • Continuously computed impact point (digital) • LORAN C/D • Aided visual display (telescope, FLIR) • Air-to-air missile capability 	<ul style="list-style-type: none"> • Coherent radar (30 mi) with high-resolution sq. int) • Integrated multisensor display (head-up, available to either crewman without hood; moving strip map; freeze capability) • Improved inertial navigation (0.5 nmi/hr) • Central analog-digital converter 	<ul style="list-style-type: none"> • ~ \$1 million per set • ~ \$3 million per set 	
COST GROWTH				
Sources		Reasons		
<u>Technical</u>				
• Display		Pressed technology beyond capability or need (from human-factors point of view)		
• Radar		Based on laboratory devices never developed, integrated, or tested		
• Analog-digital converter		Pressed state of the art (went from simple to coherent with squint; range required went from 15 mi to 30 mi). Cooling problems necessitated changes in aircraft		
• Inertial navigation system		New component development and system integration, across the board		
<u>Management</u>		Pressed state of the art. Underbid		
• Disagreements on requirements		Service R&D senior headquarters staff conservative; air staff and contractor ambitious. Uncertainty not allowed for		
• Contract structure		Prime-sub-sub compounded overhead and fees, increasing cost 40% in management alone		

TABLE C-2. C-5A NAVIGATION SUBSYSTEM

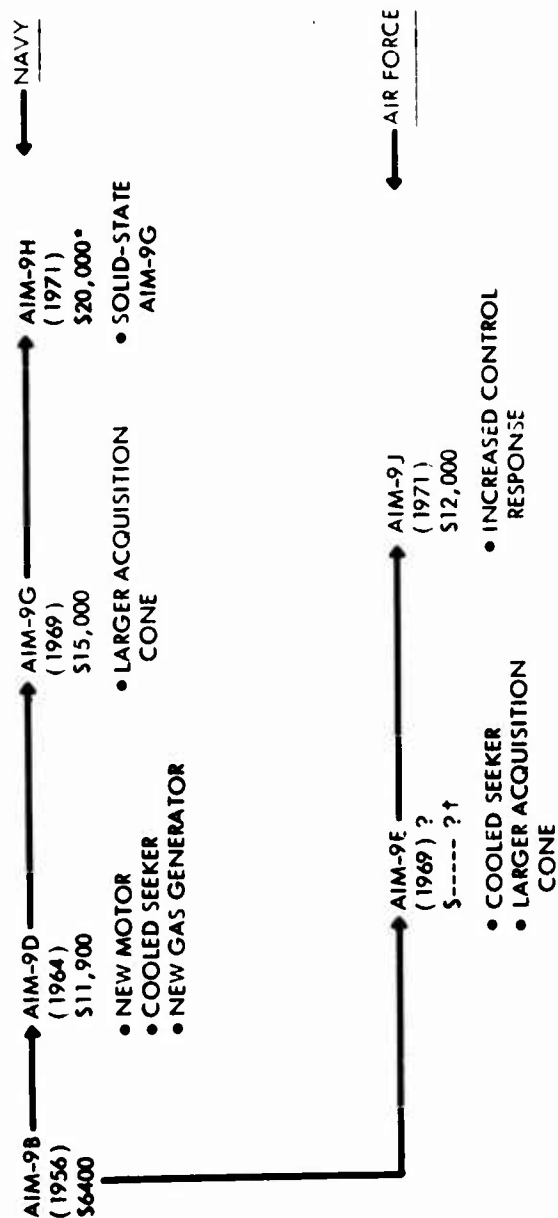
<u>Original Requirement</u>	<u>Changes, Before Approval</u>	<u>Cost Growth</u>	
		<u>Estimate</u>	<u>Ultimate</u>
Radar: Terrain avoidance & following. Weather. Assist in checkpoint navigation.	Dropped unattended airfield requirement Reduced accuracy	Radar: \$380,000 Inertial: \$100,000	~ \$1.5 million ~ \$400,000
Accuracy: 300 ft at unattended airfield after distant checkpoint	Allowed use of inertial system only, with beacon for terminal guidance		
New stellar-inertial system			

<u>COST GROWTH</u>	
<u>Sources</u>	<u>Reasons</u>
Radar	Specification for radar led to poor matching of pulse repetition rates, pulse widths, bandwidth. Information rate and bandwidth not matched for interferometric terrain-following scheme Poor initial design in light of above problems. SPO insistence on adhering to SOT
Inertial	Specification required development of new floating-ball gyro technology; subcontract from prime to subcontractor for system; prime contract precluded USAF intervention

contractor. The radar performance requirement may also have been extreme for an aircraft of this type and mission, since it is questionable whether it would ever be put in a position where terrain following is necessary. The system project office was unwilling to reduce the performance specifications for the radar to keep costs down. Yet, in both cases (radar and INS), the argument could have been made (and later would be borne out by experience in Vietnam with C-141s) that an aircraft of this type and cost would operate in a reasonably protected environment, therefore decreasing the need for a completely self-contained, ultrahigh-performance navigation system.

C. AIR-TO-AIR MISSILES

This examination considered the AIM-9 series of missiles. Figure C-1 shows the progression of characteristics and costs with time (the costs are approximate, having been derived to a great extent by inference from fragmentary data³). Note the division into Air Force and Navy versions, resulting from an early Navy decision to adopt a new launcher having the cryogenics for the seeker in the launcher rather than in the missile. Each Service was, as a result, unable to use the other's missiles, adding cost, complicating inventory problems during the Vietnam war (at some cost which could not be estimated), and giving up some of the cost reduction that would have derived from extending the production learning curves. When the Deputy Secretary of Defense ordered compatible missiles for both Services, the different Air Force and Navy launcher philosophies required the Air Force version of the AIM-9L missile to include a coolant bottle in the missile, while the Navy missile retains an empty module with piping from the launcher. Missiles must be adapted for each Service at their respective depots. Thus, by incidental decisions regarding requirements for launcher and missile types, separately made in each Service, the entire system has been more expensive over its useful life than it would otherwise have been.⁴



*First buy; 1973 buy, \$10,200.

†Data not available from sources used.

FIGURE C-1. AIM-9 Evolution (Data from Ref. 3; costs estimated from incomplete data in Ref. 3 and normalized to 1972 dollars; unit flyaway cost estimates shown, not normalized for production run.)

D. MAIN BATTLE TANK⁵

Figure C-2 shows the cost of a succession of tanks, and the division of costs between the fire-control system and the remainder of the tank. The added fire-control functions that led to increased costs are also shown. The figure indicates that electronic system costs grew much faster than those of the remainder of the tank, despite significant changes in armament, armor, suspension, and propulsion. A significant aspect of how requirements statements can be changed by arbitrary circumstances is shown by the difference between the canceled XM-803 tank and the new XM-1 main battle tank just entering development. From virtually the same available information (on infantry antitank weapons to be available, on anti-tank helicopters in development, on tactical aircraft antitank weapons available or in development, and on projected Soviet tank numbers and characteristics), it was decided that the XM-803 needed a missile for the antitank defense role, while the XM-1 did not need it, since the XM-1 would operate in an offensive role only and other antitank systems would defend it against tank attack.⁶ The driving force in this change of outlook was the Congressional instruction on how much the tank should cost.⁷ In addition, the earlier approach to the day-night sight, which was an important factor in XM-803 fire-control system cost, was expensive.⁸ This cost will be reduced in the XM-1, since thermal imaging has become available to replace the laser technology that was initially pursued. It can be supposed that if the tank had been developed using state-of-the-art fire-control technology, with later incorporation of more advanced technology after it was proven, the overall costs would have been lower. The historical outcome suggests that the electronic subsystem development should not, in this case, have been tied to the IOC of the main tank assembly.

E. ARMED HELICOPTER

This case was examined in the greatest detail of all the examples considered here because it is of current interest, the data

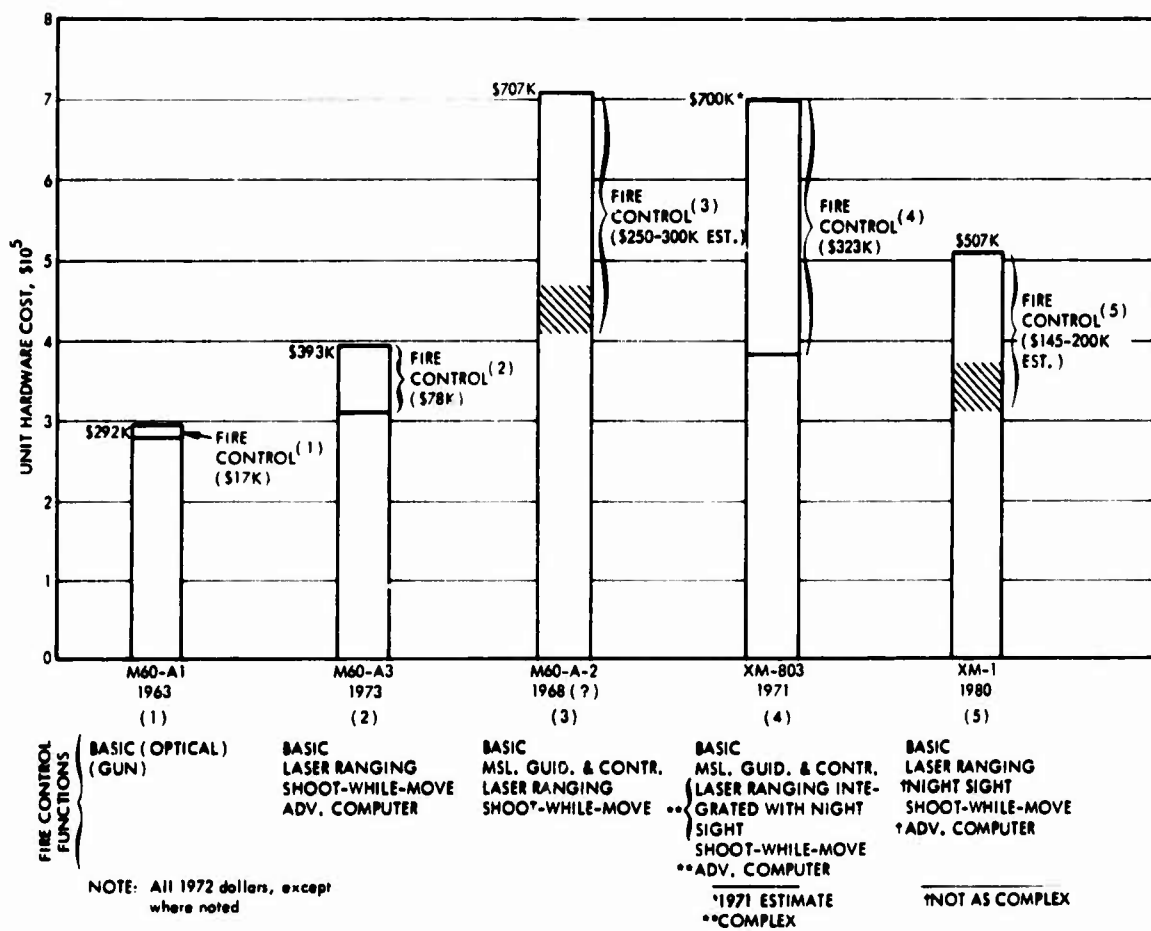


FIGURE C-2. Tank Fire-Control Costs and Functions⁵

were available, and the armed helicopter was found to typify many current major-system requirements problems. The following discussion is not meant to critique the Army's program, since the program is a current design-to-cost program and is considered to be well and carefully managed. The information and discussion are presented for their intrinsic interest and as lessons in the requirements process. The main concern here is with electronics; other factors will be mentioned when relevant.

Current Army armed helicopters date back to the early 1950s, having begun with the H-21 and H-40 series transport and utility helicopters.⁹ The H-40 became the UH-1 and, after considerable experimentation, acquired a succession of standard armaments for combat in Vietnam. The UH-1 was modified to become the COBRA, and improvements of the latter are to be extended into the future Army force structure. The COBRA, at the end of a long line of development, has growth limitations. The attempt to initiate a new-generation machine led to the AH-56 CHEYENNE, which was canceled because its unit cost became too high. The requirement for the AH-56 did not specify the fire-control system in detail, and that subsystem evolved during development. Additions included such equipment as a laser range-finder/designator, TOW fire control, a helmet sight, and an advanced fire-control computer.¹⁰ Of a development overrun of \$205 million, about \$110 million was due to changes resulting from engineering and design problems. While much of this was due to rotor instability at high speed, some was attributed to the addition of TOW, night-vision systems, and avionics changes.¹¹ In addition, it was found (among other problems) that of a \$49.5 million GSE buy necessary to support the first 15 aircraft, \$26 million would have been required for test sets for the Doppler heading-attitude reference system (the expenditure was deferred). These test sets had not been anticipated when the Doppler navigation system was chosen.¹²

The Army attempted to rectify these problems when the new Advanced Attack Helicopter (AAH) was planned.¹³ Table C-3 lists some

key requirements areas contained in the DCP for the AAH. These are expanded in the "materiel need" document,¹⁴ which gives fire-control and related avionics specifications in more detail than was the case for the AH-56.* Table C-4¹³ shows the bases of choice among competing systems, presented in the DCP, leading to the recommendation for a new AAH development as the preferred choice over two other alternative systems based on existing aircraft. Table C-5¹⁵ lists several areas in which attempted adherence to the requirements could lead to increased costs, and also in which the choice of the preferred aircraft could be reversed if projected cost-effectiveness were the only basis of choice. It will be noted that the desired kill probability against tanks is more optimistic than data from simulated field-test engagements between armed helicopters and tank companies would suggest, and that predicted exchange ratios from those tests are less optimistic than the ratios forecast for the new machine in the DCP. In the case of mission reliability, the data that might support the reasonableness of the requirement do not exist. Note, also, that the new aircraft was claimed, in the DCP, to entail lower development risk than would a further adaptation of the COBRA. Although good reasons why this might be so were given, risk as such was stated, without backup, as "high," "medium," or "low." Prima facie, the proposition is counterintuitive.

Thus, without arguing that the wrong choice was made, or that the planned aircraft development cost or unit acquisition cost will be overrun, it is apparent that the design may be difficult to hold to cost unless there is great management flexibility to adjust the requirements, and unless management is aware of the pitfalls and monitors the development closely. Note that total force procurement plans include both alternatives, so that in any case the Army's options will be retained.

* Ten statements described specified fire-control functions for the AH-56, as opposed to 21 statements for the AAH, based on Ref. 14 and the AH-56 QMR.

TABLE C-3. KEY ADVANCED ATTACK HELICOPTER REQUIREMENTS

(Quantitative values not shown)

1. Agility
2. Armor protection
3. Overall system reliability for ___-hr mission, ___%
4. Weapon P_k , associated with conditions (day, night, weather, target and behavior)
5. Night-operating systems and fire control
 - Specified separately for pilot and copilot-gunner
 - Detection and recognition ranges, by condition and target
 - Displays described
 - Field of view and resolution specified

TABLE C-4. BASES FOR CHOICE AMONG THREE ADVANCED ATTACK HELICOPTER ALTERNATIVES

- One existing system ruled out for reasons of:
 - Cost, competition, other limitations
- Between other existing system (improved) and new system:
 - New system more agile
 - Vulnerability
 - Cost-effectiveness

$\left. \begin{array}{l} \text{Vulnerability} \\ \text{Cost-effectiveness} \end{array} \right\} \begin{array}{l} \text{New system costs more but} \\ \text{is more cost-effective} \end{array}$

- New system has more performance flexibility
- New system has less technical risk (reasons given involve systems integration and potential structural problems)
- New system has more growth potential

TABLE C-5. ADVANCED ATTACK HELICOPTER: AREAS THAT CAN
DRIVE COST OR REVERSE SYSTEM CHOICE^a

1. P_k (and conditions) in DCP, requirement document, and RFP all differ and are all higher than demonstrated in OT&E simulating combat
2. Weather and detection/recognition probabilities for E/O systems not specified; could lead to overdesign for worst conditions
3. Mission reliability specification based on theoretical MTBF, not supported by data for simpler systems in SEA
4. Fire control and avionics can be complicated by armor specification affecting internal configuration of aircraft
5. Exchange ratio from OT&E^b differs enough from exchange ratio from the models used for justification to make competing systems equally cost-effective within the uncertainty.
6. Risk may be underestimated for new system, in terms of unanticipated problems versus known problems for existing system

^aNot discernible from DCP, alone.

^bSimulated helicopter-tank combat.

F. LORAN D¹⁶

LORAN C was designed for overwater navigation to provide a great increase in accuracy over the original LORAN A hyperbolic navigation system. In LORAN C, position was determined by referring time-difference readouts to specially prepared charts. It was noted that the system could be adapted for overland use and would provide tactically usable accuracies, at shorter range, if a shorter transmitter baseline were used, with corresponding changes in pulse repetition rate and signal structure, and with signal sampling point delayed. This revised system was designated LORAN D. In addition, the Air Force decided to incorporate automatic tracking, continuous coordinate-conversion by computer, and advanced integrated circuits to reduce the size and weight of the airborne equipment. The new equipment was tested at Eglin Air Force Base and demonstrated problems that could not easily be separated because the basic design of the LORAN receivers, the system functions, and the electronic technology had all been changed simultaneously.

Thus, when a navigation system was needed in Vietnam, the Army installed DECCA, which had less accuracy but was an available, operating system. At the same time, continuing LORAN D problems were raising the cost for the airborne equipment (receiver plus computer) to about four times the original estimate. By a special effort, stimulated by the Air Force R&D senior headquarters staff, the avionics cost was reduced, although not to the original value. (That was reached in subsequent years.) However, there was as yet "no requirement."

At this point, the Defense Communications Planning Group, needing an accurate navigation system for emplanting and locating sensors on the Ho Chi Minh Trail, requested that the Air Force install LORAN in Southeast Asia. LORAN C transmitters were used. One squadron of F-4s equipped with the ARN-92 LORAN D receiver, which could also receive and use LORAN C signals, was deployed in 1968. Later, two more squadrons were equipped, for night bombing in conjunction with

sensor information. Currently, LORAN D is one of the systems for radio navigation that is being considered for Air Force and Army use in Europe, for auxiliary updating of inertial systems, for use by ground troops, and for other applications.

One feature of the development was the fact that at no time was the annual program cost high enough to make the development visible as a "major system." Therefore, those in the Air Force who saw its potential value were able to fund it as an independent development, illustrating the value of leaving "openings" in control of development funds to allow for innovation.

G. PAVE SPIKE

PAVE KNIFE was the original laser designator pod designed for F-4 delivery of laser-guided bombs (LGBs) and deployed to Southeast Asia. PAVE SPIKE is the improved version--smaller, better fitted to the aircraft, and with greater capability to assist F-4 weapon delivery. The original PAVE KNIFE pods were R&D items. When the Air Force wanted additional pods, it was initially quoted a production price of approximately \$500,000 per pod. Therefore, it was decided to hold a competition for a new production system, which resulted in the December 1970 award of a \$3.3 million fixed-price, total-package-procurement development contract for three prototype pods, appropriate F-4D modifications, and two sets of prototype AGE. The associated production cost bid in the development contract was between \$100,000 and \$200,000 per pod for a production buy. There was a contract time limitation on the production options, and the development contract did not include a procurement data package until a production option was exercised. Thus, when the Air Force decided to freeze the R&D design in June 1972 and to acquire a modest number of pre-production pods for a quick-reaction-capability Southeast Asia combat requirement, it was not in a favorable position to hold a production competition. The pre-production pods cost more than twice the original (tentative) production bid price associated with the

maximum production option. Current plans are to acquire a large production quantity of pods and to modify a number of F-4s to use them. The price for the pods alone is now less than \$200,000 each. The total production contract also has "not-to-exceed" costs for ECPs, AGE, aircraft modification kits, and a data package.¹⁷

Although the above procurement represents final Air Force plans at the time of writing, the additional quantities of LGB delivery systems that might be acquired, it may be inferred, nevertheless remain uncertain, as a result of potential application to other aircraft. For example, pods may ultimately be desired for use on such aircraft as the F-111 and A-6. The pod is designed for use on two-seat aircraft; automatic target tracking would be needed for the system to work with the A-7 (a single-seat aircraft) or, later, the A-10, if the A-10 enters the force. Providing a two-seat version of such aircraft, or using any two-seat aircraft with a pod to designate, could also enable single-seat-aircraft LGB delivery, and would be necessary if the pod is not modified. For such additional uses, additional costs are in the offing due to uncertain current programming of the total number of LGB delivery systems and associated aircraft modifications. Thus, although the LGB capability exists and is proven, DOD cannot take full advantage of the potential cost savings of a long production run and efficient aircraft design modifications for use on all of the relevant aircraft of all Services, because plans for incorporating the capability in the total DOD force structure have not been made. (Of course, it may not be possible to make such plans, and other costs could be incurred while attempting to save in this area, if there is insufficient prescience about what will be required in each aircraft system.)

H. COMPASS EAGLE¹⁸

This program illustrated how costs can be incurred indirectly when a capability exists but is not used because there is "no requirement." COMPASS EAGLE attempted to improve the quality of information

obtained by infrared (IR) scanners on reconnaissance aircraft. COMPASS EAGLE was undertaken in the mid-1960s as a joint ARPA-RADC(USAF) effort, and one of its outputs involved substitution of magnetic tape for the normal film on which IR data are recorded. The data could then be read directly from the tape, leading to about a three-fold improvement in resolution (i.e., permitting the scanner to operate near its design resolution, which did not normally occur). With the hardware development went the development of photo-interpretation techniques to make better use of the IR "take," since it had been observed that normal IR reconnaissance yielded little useful data, especially in relation to the expenditures for the missions.

The COMPASS EAGLE system was flown in Vietnam as part of an RB-57 reconnaissance system test, and its effectiveness (including the potential gain in the utility of the IR data) was demonstrated. However, the 7th Air Force did not express a requirement for it, and therefore it was used only for the R&D and demonstration flights. The cost of modifying two squadrons of RF-4 aircraft to incorporate the new capability would have been about \$500,000; the RDT&E cost was about \$3.5 million. The estimated cost of the IR reconnaissance missions of those squadrons for 3 years might have been about \$25 million.* Thus, the expenditure of about \$4 million could have greatly improved the effectiveness of about \$25 million spent on operations, but was not undertaken for lack of a formal "requirement."

I. E-2C AIRCRAFT¹⁹

The key steps in the development of this program are shown in Table C-6. While this program was originally examined in this study

* Estimate of \$25 million assumes: five infrared reconnaissance sorties per day, at 1 to 2 hours each; O&M cost of \$1000 per flying hour; 0.1 percent attrition of RF-4, at about \$3 million each; 3 years of operation; and \$300,000 per year for operation of IR part of reconnaissance data interpretation and analysis center.

simply to ascertain what fraction of the program's cost has been devoted to electronics, an aspect of the program emerged that makes it relevant in the context of the requirements-acquisition decision process. The E-2A aircraft was operated with the APS-96 search radar (state of the art about 1960) for sea search while development of a new radar with an overland capability proceeded separately. When a new radar (APS-111) emerged from development (in which there had been informal competition between two sources), this was put into production as the APS-120 for the E-2C. Thus, a wholly new capability for the system mission was integrated into an existing platform. The platform power plant was uprated in thrust at the same time, but development of a completely new system was found to be unnecessary.

TABLE C-6. KEY POINTS IN E-2C HISTORY

- Initial operational capability, E-2A: 1964
- Improved computer, E-2B: 1969
- Studies, one funded by DOD and one contractor-funded, of overland radar: 1960-61
- AN/APS-111, RDT&E: 1963-1966
- AN/APS-120, production radar testing completed: 1969
- Initial operational capability,^a E-2C: 1973

^aIncludes engine and navigation system upgrade.

REFERENCES AND NOTES FOR APPENDIX C

1. Information on the Mark II avionics for the F-111 was obtained from discussions with A. H. Flax and L. M. Biberman, of IDA, and H. Davis, consultant. The writer (S. Deitchman) is responsible, however, for any misstatements or omissions of pertinent facts that may be noticed by knowledgeable readers.
 2. Information on the C-5A navigation subsystem was obtained from A. H. Flax, of IDA, and H. Davis, consultant. The writer (S. Deitchman) is responsible, however, for any misstatements or omissions of pertinent facts that may be noticed by knowledgeable readers.
 3. Report of the Ad Hoc Working Group of Air-Air Missiles, July 1970, Chapters VII, XI.
The unit flyaway cost numbers shown here were reviewed by T. Rucker, Price and Cost Analysis Section, Naval Weapons Systems Command. While the numbers shown are not precisely the ones he would find in the record, he believed they were not unreasonable as approximations to actual costs.
 4. Discussion of AIM-9 based on Electronics-X Working Paper 14, available at the IDA Library.
 5. Main battle tank data were obtained from:
 - U. S. Army, Main Battle Tank Task Force, Final Report, Part I, Executive Summary, Part V, Parametric Cost Analysis, 1 August 1972.
 - MBT Issues Papers, obtained from Combat Vehicles Systems Office, Director of Systems, ACSFOR, U. S. Army.
 - Office of the Comptroller of the Army, XM-803 Cost, Memorandum, 12 February 1971.
 - Development Concept Paper 117 for the New Army Battle Tank, 26 December 1972.
- In Fig. C-2, the costs shown as estimated were not available from the above sources but were inferred from known data for other tanks and by comparison of fire-control functions. These estimated fire-control-system costs could be in error by approximately ± 25 percent.
6. Development Concept Paper 117, cited in Ref. 5 above.

7. House of Representatives, 92nd Congress, 1st Session, Department of Defense Appropriation Bill, 1972, Report 92-666, pp. 73-75.
8. Memorandum of the Comptroller of the Army, cited in Ref. 5 above.
9. Lt. Col. C. O. Griminger, "The Armed Helicopter Story," Army Aviation Digest, July-December 1971.
10. Conversation with personnel of Aircraft and Avionics Weapons and Support Systems Office, Director of Systems, ACSFOR, U. S. Army.
11. CHEYENNE Selected Acquisition Report, 31 March 1972, pp. 7-9.
12. Army Electronics Command, Support Alternatives for Avionics System of CHEYENNE Aircraft, Memorandum, 15 March 1969.
13. Development Concept Paper 123 for the Advanced Attack Helicopter, draft "for coordination," 28 March 1973.
14. Army Combat Developments Command, Advanced Attack Helicopter Materiel Need (Engineering Development), Control Number 20268, November 1972.
15. Obtained from comparison of data and specifications given in Refs. 13 and 14, as well as:
 - Advanced Attack Helicopter, RFP DAJ01-73-R-0179 (P40).
 - Institute for Defense Analyses, Operational Test and Evaluation of the Air Launched TOW Missile System, IDA Study S-412, L. G. Starkey et al., January 1973.
 - Discussions with personnel of Army Aviation Systems Command, Product Assurance Office (AMSAV/LSA), St. Louis, Missouri.
16. Information on the history of LORAN D was obtained from V. Weihe and H. Davis, consultants. The writer (S. Deitchman) is responsible, however, for any misstatements or omissions of fact that may be noticed by knowledgeable readers.
17. The foregoing information on PAVE SPIKE was provided by the Tactical Applications Branch, Aeronautical Systems Division, Directorate of Development and Acquisition, Deputy Chief of Staff, USAF. The subsequent discussion of potential PAVE SPIKE requirements should not be attributed to that office.
18. The work of ARPA in association with the Rome Air Development Center's COMPASS EAGLE program was under the cognizance of the writer, S. Deitchman, when he was with ARPA (1966-1969). The discussion of COMPASS EAGLE is based on the writer's recollection. The COMPASS EAGLE infrared reconnaissance system is described in:

Institute of Science and Technology, University of Michigan,
Ann Arbor, COMPASS EAGLE Infrared Reconnaissance System,
A. K. Parker, November 1968.

19. Information on the E-2C was obtained from: DCP 26, Revision 1, 24 June 1971; SAR, March 1973; and E-2C Program Office (Electronics-X Memorandum by C. Weissman, 24 August 1973).

APPENDIX D

**ELECTRONICS-X WORKING PAPERS
AND SUBCONTRACTOR REPORTS**

ELECTRONICS-X WORKING PAPERS*

8. Warranties/Contractor Maintenance, D. Arnold, 14 June 1973. (IDA Log HQ 73-15189/3)
9. Motivations and Incentives in the Weapons Acquisition Process, Vols. I & II, W. Allen, June 1973. (IDA Log HQ 73-15689/1)
12. Case No.: Warranties-1. Cost Comparison of Contractor Warranty versus Military Maintenance for Several Inertial Navigation Systems, D. Arnold, 15 June 1973. (IDA Log HQ 73-15198/1)
13. Case No.: Warranties-2. Comparison of Maintenance Cost, Reliability, and Complexity of USAF Military Airlift Command versus Commercial Airline Weather Radars, D. Arnold, 20 June 1973. (IDA Log HQ 73-15201/1)
14. AIM-9 Case Study (U), L. Biberman, 22 June 1973 (S). (IDA Log HQ 73-15233/1)
16. Electronics-X Program Design to Cost, J. Norman, 11 July 1973. (IDA Log HQ 73-15265/1)
17. Configuration Management, D. Arnold, 18 July 1973. (IDA Log HQ 73-15288/1)
19. Contractual Aspects of Design to Cost, H. Zimmerman, 20 July 1973. (IDA Log HQ 73-15298/1)
21. Standardization, R. Polkinghorn, V. Weihe, and C. Rauch, 3 August 1973. (IDA Log HQ 73-15342/2)
23. Appendices to the Electronics-X Standardization Report, R. Polkinghorn, V. Weihe, and C. Rauch, 14 August 1973. (IDA Log HQ 73-15379/1)
24. Institutional Incentives, D. Soergel, 24 August 1973. (IDA Log HQ 73-15429/1)
27. Project Management (Revised), M. Clyman and B. Gourary, 28 November 1973. (IDA Log HQ 73-15668/2)

*The numbered working papers missing from this list are regarded as of only temporary interest.

28. Maintenance and Competition in a Zero Draft Environment,
T. Rowan, 20 August 1973. (IDA Log HQ 73-15676/1)
29. Job Performance Aids and Maintenance, T. Rowan,
22 August 1973. (IDA Log HQ 73-15675/1)
30. Planning, Programming, Budgeting--The Requirements Process,
C. Weissman, 15 August 1973. (IDA Log HQ 73-15685/1)
31. Electronic Equipment Maintenance in the Department of
Defense, J. Morgan and F. McDonald, 30 September 1973.
(IDA Log HQ 73-15700)
32. System Design to Minimize Spares Costs, H. Gates,
7 May 1973. (IDA Log HQ 73-15701/1)
33. Relative Dollar Volume of Various Classes of Avionics,
H. Gates, 23 May 1973. (IDA Log HQ 73-15702/1)
34. Relative Dollar Volume of Various Classes of Equipment,
H. Gates, 6 June 1973. (IDA Log HQ 73-15703/1)

ELECTRONICS-X SUBCONTRACTOR REPORTS

1. Arinc Research Corporation, An Analysis of Electronics "Standard Module" Programs, Final Report--Electronics-X Report, C. Postlewaith, July 1973. (IDA Log 73-148 834)
2. Arinc Research Corporation, The User-Technologist-Industrial Approach to Electronic Equipment Specifications and Procurement, Final Report--Electronics-X Project, G. Boring, July 1973. (IDA Log 73-148 833)
3. Ketron, Incorporated, An Analysis of Field Reliability and Maintainability Information Channels, T. Hedberg, 31 August 1973. (IDA Log 73-149 686)
4. Ketron, Incorporated, The Change Process in Weapons Systems Acquisition, W. J. Douglas, 3 August 1973. (IDA Log 73-149 687)
5. Information Spectrum, Incorporated, Procurement of Unnecessaries, M. Clyman and M. Green, 22 August 1973. (IDA Log 73-148 945)
6. Information Spectrum, Incorporated, Direct Technical Approaches to Cost Reduction, M. Clyman and M. Wilson, 22 August 1973. (IDA Log 73-148 946)
7. Information Spectrum, Incorporated, Cost of Electronic Equipment Reliability, R. Shultz, 22 August 1973. (IDA Log 73-148 947)
8. Information Spectrum, Incorporated, Reliability Specifications, R. Shultz, 22 August 1973. (IDA Log 73-148 948)
9. Information Spectrum, Incorporated, Cost Estimating Techniques and Cost Analysis Data System, M. Clyman and D. Weiss, 1 August 1973. (IDA Log 73-148 949)
10. System Development Corporation, Standardization of Avionics Information Systems, 31 August 1973. (IDA Log 73-148 200)

APPENDIX E

SOURCE DATA FOR FIGURE II-5

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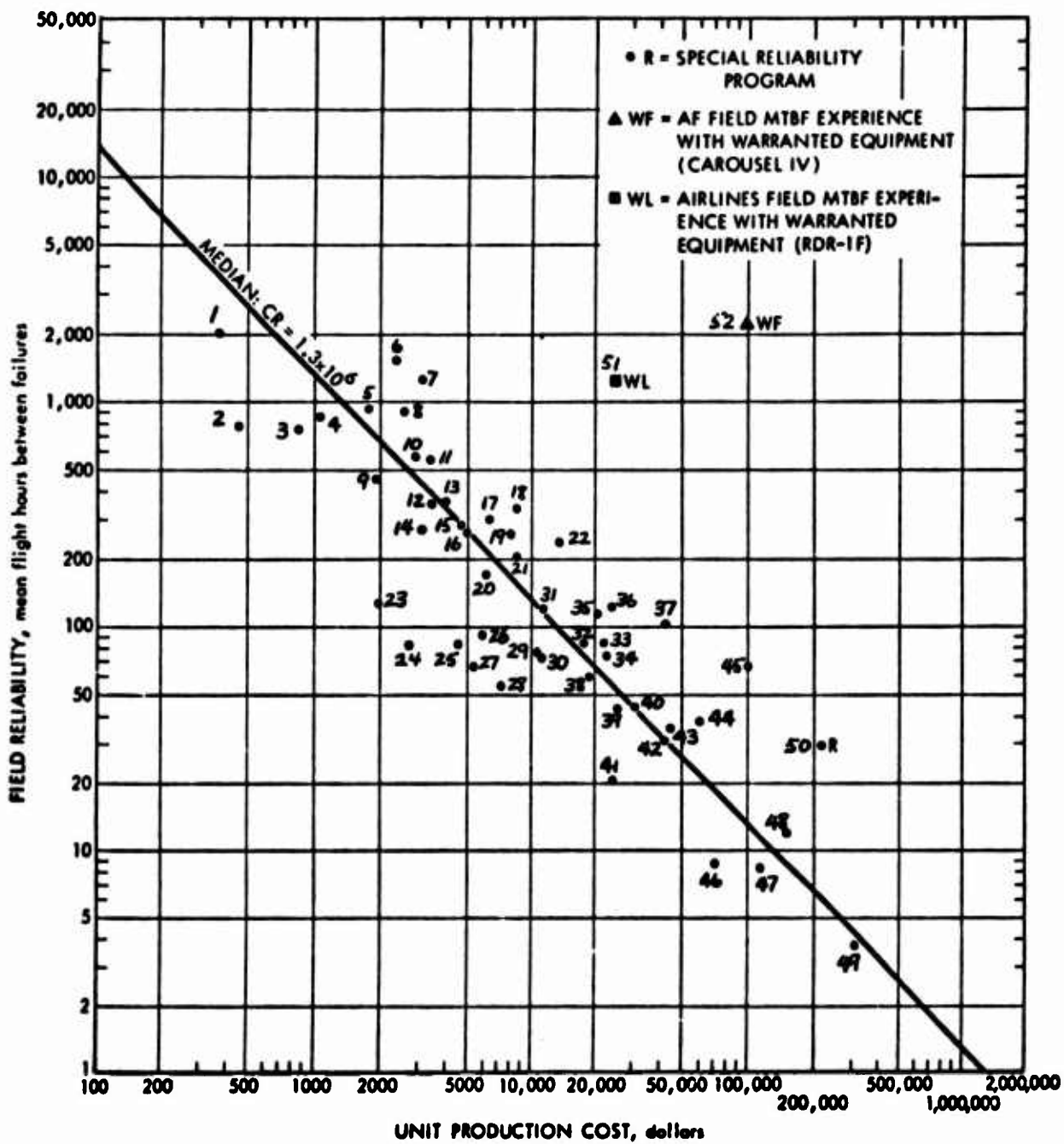


FIGURE II-5. Avionics Field Reliability versus Unit Production Cost
 (Data points keyed to items listed in the accompanying table.)

SOURCE DATA FOR FIGURE II-5

Item	Nomenclature	Unit Production Cost, dollars	Relia- bility, MFHBF	Source
1	51Z3 Marker Beacon	\$ 372	2,045	Ref. 1
2	ARN-18 Glide Slope Indicator	450	772	Ref. 1
3	ARN-31 Glide Slope Indicator	852	756	Ref. 1
4	ARN-32 Marker Beacon	1,038	857	Ref. 1
5	ARN-12 Marker Beacon	1,757	941	Ref. 1
6	ARN-67 Glide Slope Indicator	2,381	1,623	Ref. 1
7	51R-6 VOR	3,069	1,259	Ref. 1
8	51V4/WIL-800B Glide Slope Indicator	2,550	918	Ref. 1
9	ARN-58A VOR	1,896	443	Ref. 1
10	APX-64 IFF	2,891	567	Cost: Ref. 2 Reliability: Ref. 1
11	FM-622A VHF Communication System	3,348	556	Ref. 1
12	DFA-73B Direction Finder	3,380	351	Ref. 1
13	WIL-807A VHF Communication System	3,780	355	Ref. 1
14	WIL-806A VOR	3,069	275	Ref. 1
15	HF-102 HF Communication System	4,579	288	Ref. 1
16	ARN-14 VOR	4,906	265	Ref. 1
17	VOR-101 VOR	6,365	300	Ref. 1
18	HF-101 HF Communication System	8,270	342	Ref. 1
19	CP-953/ASQ A-7E Air Data Computer	8,000	258	Ref. 3
20	DFA-70B Direction Finder	6,073	170	Ref. 1
21	VHF-101 VHF Communication System	8,270	206	Ref. 1
22	ARC-90 UHF Communication System	13,700	242	Cost: Ref. 2 Reliability: Ref. 1

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SOURCE DATA FOR FIGURE II-5 (Continued)

Item	Nomenclature	Unit Production Cost, dollars	Relia- bility, MFHBF	Source
23	APX-25 IFF	\$ 1,962	126	Ref. 1
24	APN-70B LORAN	2,686	72	Ref. 1
25	ARC-34 UHF Communication System	4,594	83	Ref. 1
26	ARN-21C TACAN	5,929	91	Ref. 1
27	ARC-133 UHF Communication System	5,332	67	Ref. 1
28	ARN-52 TACAN	7,376	54	Ref. 1
29	ARN-58 HF Communication System	10,486	78	Ref. 1
30	ARC-109 UHF Communication System	11,180	71	Ref. 1
31	ARC-105 HF Communication System	11,700	121	Ref. 1
32	ARC-65 HF Communication System	18,000	83	Ref. 1
33	ARC-112 HF Communication System	22,576	86	Ref. 1
34	APN-147 Doppler Navigator	22,794	73	Ref. 1
35	APN-81 Doppler Navigator	20,435	113	Ref. 1
36	C-8185/AWE A-7E Armament Station Control	24,000	121	Ref. 3
37	APN-151 LORAN	41,639	102	Ref. 1
38	APN-89 Doppler Navigator	18,804	60	Ref. 1
39	ASN-99 A-7E Map Display	26,000	42.6	Ref. 3
40	APN-157 LORAN	36,226	43	Ref. 1
41	APN-190 A-7E Doppler Navigator	24,000	20.6	Ref. 3
42	AVQ-7 A-7E Head-Up Display	42,000	31.6	Ref. 3
43	APN-59B Weather Radar	45,000	35	Ref. 4
44	ASN-90 A-7E INS	61,000	38.4	Ref. 3
45	ASN-91 A-7E Navigation/Weapon Computer	101,000	68.6	Ref. 3

SOURCE DATA FOR FIGURE II-5 (Continued)

Item	Nomenclature	Unit Production Cost, dollars	Relia- bility, MFHBF	Source
46	APQ-126 A-7E Radar	\$ 71,000	8.9	Ref. 3
47	APN-92 LORAN	113,000	8.4	Ref. 1
48	APQ-120 Complete Fire Control	152,000	12	Ref. 4
49	AWG-10 Radar and Fire Control	312,000	3.8	Ref. 4
50	APQ-113 Radar	218,000	29.5	Ref. 4
51	RDR-1F Weather Radar	25,000	1,259	Ref. 4
52	CAROUSEL IV EC-134J INS	100,000	2,208	Ref. 5

REFERENCES

1. Arinc Research Corporation, Cost Study of Selected Communications, Navigation, and Identification Equipments, OEO-01-1-1190, June 1972.
2. Rome Air Development Center, AFSC, AF RAD 043.
3. A-7 Project Manager.
4. David Arnold, Westinghouse Defense and Electronic Systems Center, Baltimore-Washington International Airport, Maryland.
5. Delco Division, General Motors Corporation.

APPENDIX F

DISCUSSION OF WEIGHTING METHOD EMPLOYED IN CALCULATING AVERAGE PROGRAM COST GROWTH AND ITS STANDARD DEVIATION

DISCUSSION OF WEIGHTING METHOD EMPLOYED IN CALCULATING AVERAGE PROGRAM COST GROWTH AND ITS STANDARD DEVIATION

Tables III-2 and III-3 show the program cost growth of a number of weapons systems in development and production. Table III-2 shows cost growth during 4 years of development, and Table III-3 shows cost growth during 4 years of production. Cost growth is measured from the earliest available estimate--from the planning estimate, if it is available; otherwise, from the development estimate.

Because of the nature of the data and the fact that for any given time data are usually unavailable for some program or programs, the summary calculations are based on a slightly changing mix of programs.

To provide a reasonable perspective of program cost growth without overemphasizing the importance of the small programs, a mean and a standard deviation were calculated for each set of data by a least-squares procedure in which each program was weighted in proportion to its initially estimated cost. The weighting is explained below.

The following notation was used:

i denotes the particular program on the i^{th} line of the table.

n is the number of programs.

p_i is the planning estimate of the cost of the i^{th} program. If no planning estimate is available, the development estimate $c_i^{(d)}$ is used in its stead.

$c_i^{(k)}$ is the current estimate of the cost of the i^{th} program. Thus, $c_i^{(d)}$ is the development estimate, $c_i^{(1)}$ is the current estimate during the first reported year, $c_i^{(2)}$ is the current estimate during the second reported year, and so on.

$x_i^{(k)} = c_i^{(k)} - p_i$ is the estimated cost growth of the i^{th} program from its initial cost estimate.

$u_i^{(k)} = x_i^{(k)} / p_i$ is the estimated cost growth of the i^{th} program expressed as a fraction of the initial cost estimate.

w_i is the weighting factor associated with the i^{th} program to make up for the fact that different programs entail different amounts of money. The weighting is proportional to the initial estimate of the dollar value of each program. Thus,

$$w_i = p_i / \sum_{j=1}^n p_j = p_i / n\bar{p} ,$$

where

$$\bar{p} = \frac{1}{n} \sum_{j=1}^n p_j .$$

Note that

$$\sum_{j=1}^n w_i = 1 .$$

Note that \bar{p} must be computed individually for each set of data, because the data are incomplete, and not all programs are reported in every set. Thus, the correct expression is really $\bar{p}^{(k)}$. Also, $n^{(k)}$ must be used; consequently, $w_i \rightarrow w_i^{(k)}$.

The two important characteristics of the sample are:

1. The average program cost growth trend line, points on which are given by

$$\langle u^{(k)} \rangle = \sum_{i=1}^n w_i^{(k)} u_i^{(k)} = \bar{x}^{(k)} / \bar{p}^{(k)} ,$$

where one has the definition:

$$\bar{x}^{(k)} = \frac{1}{n^{(k)}} \sum_{j=1}^{n^{(k)}} x_j^{(k)} .$$

2. The standard deviation from the points on the cost-growth trend line, which is given by

$$\begin{aligned} \sigma^{(k)} &= \sqrt{\sum_{i=1}^{n^{(k)}} w_i^{(k)} [u_i^{(k)} - \langle u^{(k)} \rangle]^2} \\ &= \sqrt{\frac{1}{n^{(k)} \bar{p}^{(k)}} \sum_{i=1}^n \frac{(x_i^{(k)})^2}{p_i} - \left(\frac{\bar{x}^{(k)}}{\bar{p}^{(k)}} \right)^2} . \end{aligned}$$

The expression for the mean cost growth $\langle u^{(k)} \rangle$ is that which minimizes the weighted variance $[\sigma^{(k)}]^2$.

In Figs. III-1 and III-2, which are graphs corresponding to Tables III-2 and III-3, respectively, the several means are connected by straight line segments. The points representing one standard deviation on each side of the means are similarly connected. The resulting trend lines indicate the course of the average program cost growth with time during development (Fig. III-1) and production (Fig. III-2).